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TASK 3 (CONCEPT ANALYSIS)

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ABSTRACT

Application of multifunction display and control systems to the NASA Orbiter spacecraft offers the potential for reducing crew workload through automation of procedures, particulary thost associated with malfunctions. In addition, the display and control hardware associated with such a system can portray the necessary information to the crew in a more easily understood fashion using graphic displays as opposed to the current tabular displays. In this report, the access schema developed to access both individual switch functions as well as automated or semi-automated procedures for the Orbital Maneuvering System (OMS) and Electrical Power and Distribution and Control System (EPDCS) discussed and the operation of the system is described. Feasibility tests and analyses used to define display parameters and to select applicabnle hardware choices for use in such a system are presented and the results are discussed.

1.0 INTRODUCTION

This report describes the procedures followed and results obtained by Boeing in performing Task 3 (Concept Analysis) for NASA contract NAS9-16445, "Development of Preliminary Design Concept for Multifunction Display and Control System for Orbiter Crew Station".

1.1 Purpose

The purpose of this report is to describe the alternate design concepts developed in Task 3 and the analyses and feasibility testing done to establish the effectiveness and validity of those designs. The alternate designs and resultant testing were based on the recommended design concept of the Task 2 (Application of Technology) report.

1.2 Scope

Alternate designs, evaluations, and feasibility testing included in this report represent an analysis of both hardware and software and of the human factors engineering associated with the development of an efficient Multifunction Display and Control System (MFDCS)for application to the Orbital Maneuvering System (OMS) and Electrical Power Distribution and Control System (EPDCS). The testing program and alternate design development, while specifically directed to the OMS and EPDCS, are applicable to a broader range of Orbiter systems. In general, the most efficient use of the MFDCS would involve incorporation of the central Orbiter displays and controls into the system. Within the scope of this contract however, the design covers only the OMS and EPDCS and minimizes the impact on current Orbiter hardware and software.

1.3 Concept Analysis Process

A design concept was identified for further effort in Task 2 (Application of Multifunction Display and Control Technology). This concept employed a multifunction keyboard (MFK), a medium resolution display, and a high resolution display to permit operator interaction with multiple orbiter systems, display of checklist and emergency procedures and presentation of system status at varied levels of detail. Concept analysis in this report concerns the relative advantages and disadvantages of the various design alternatives developed to implement the selected design concept. The concept analysis procedures associated with the MFDCS design cover several different areas of activity. The primary area of concern is

the development of a hardware and human engineering design which will satisfy the study goals with respect to MFDCS function and impact on the remainder of the Orbiter hardware and software. These goals include the automation of crew interaction with checklists and procedures, reduction of the difficulty in understanding and operating the present data entry and display system, and minimization of impact on the current Orbiter hardware and software. Reliability and system redundancy are also basic considerations in formulating the MFDCS design. At the same time, the application of the MFDCS concept to the control of Orbiter systems in general must be considered. Similarly, hardware selection, analysis and/or testing is directed specifically at the application to the OMS and EPDCS in a current time frame. However, consideration is also given to hardware projected for availability over the next five years as well as hardware applicable to a more general Orbiter MFDCS revision.

1.4 Concept Testing

Those areas of the design alternative analyses which do not produce a clear conclusion are the subject of feasibility and performance testing where such testing is within the time and resource constraints of the contract. Considerable use is made of available Boeing resources and test programs underway and applicable or modifiable to the areas of concern for this program.

1.4.1 Human Factors

Several human factors aspects of the MFDCS concepts were considered during this phase. The Task 2 report identified the need for high resolution graphics displays to replace some of the heavy reliance on tabular numeric data. In defining the necessary displays, several display criteria were evaluated. One criteria group includes the resolution display size and font style required to present a legible and understandable graphic image to the operator with the available panel space. Another criteria considered was the use of color to encode information on the display. The major effort was devoted to the development of the access schema to the OMS and EPDCS functions using the MFDCS. Resolution requirements for graphic multifunction displays were evaluated using a sample drawing designed to illustrate the status of OMS components. This drawing was output in hardcopy form in formats containing 256 to 768 pixels along each axis.

The application of color was evaluated using a portion of the sample drawing used to evaluate display resolution. Several schemes for using color to encode information were considered for incorporation into this drawing and the results were compared with the black-and-white version of the drawing. Character size requirements and font style were evaluated with font considerations directed primarily at 5 x 7 fonts for use on flat panel multifunction switch legends. Numerous font studies have been conducted for CRT displays however, much of the work on fonts for flat panel dot matrix displays is relatively new.

A 5 by 7 element font for uppercase alphanumeric symbols was developed. This is a minor variant on the very effective Huddleston font.

The functions in a MFDCS can be organized in several ways. The operator can be provided access to each individual valve and relay in the system. Alternatively, the system can be partially automated so that the user selects an operating mode and the system then adjusts each valve and relay to the proper setting for that operating mode. These alternative approaches are illustrated in the discussion of the proposed MFDCS configuration and the other human factor considerations in Section 3.3.

1.4.2 Hardware and Software

A primary area of hardware and software testing is the configuration and performance of multifunction keyboard concepts developed for the MFDCS. Implementation of MFK systems directed toward flight packaging and performance are relatively new and a number of operating capabilities and parameters need to be established. In general, these capabilities will involve both hardware and software in combination. Topics included in the MFK testing include power consumption, operating speed, data transfer and storage of legends and logic linkages. In addition, testing of display formats for both medium resolution and high resolution displays is used to verify the MFDCS capability to produce the displays and as described in Section 1.4.1, to investigate the human factors parameters associated with the displays.

1.5 Summary

The report is divided into six major sections. Section 1 introduces the major activities performed under Task 3. In Section 2, alternatives with respect to human factors considerations and hardware selection are introduced. These subjects are analyzed with

respect to the Orbiter MFDCS requirements in Section 3. Feasibility testing carried out to assist in the analyses of Section 3 is described in Section 4. Section 5 discusses results obtained from-the analysis and feasibility testing as well as unresolved issues requiring additional consideration.

Basically, the results of the task suggest a design consisting of three display areas using separate displays. Full color was identified as an important feature of a high resolution CRT display for portraying dynamic graphic system status and configuration information. Full color was not found necessary for the display containing checklist information or for the display of legends on the multifunction keyboard. Power and weight reductions are achieved by using flat panel displays for these two areas. The operational structure of the MFDCS design will preserve the present capability to deal with selected single functions and will permit the operator to display and process checklists and procedures automatically or manually. In addition, caution and warning alerts will be presented in order of system impact and will allow the operator to deal with the problems in either a preprogrammed automatic fashion or through manual selection of corrective actions.

In Section 6, the program for Task 4 is outlined. References are contained in Section 7.

2.0 ALTERNATE DESIGN DEFINITIONS

Definitions of specific design alternatives for implementation of the design concept defined in Task 2 are presented in this section. A more detailed discussion of specific features of the designs is contained in Section 3 which describes the analysis of the designs carried out under Task 3. This section also includes a brief discussion of some of the major constraints and desired features associated with the design alternatives. This discussion is directed towards both human factors and hardware/software aspects of the designs.

2.1 Human Factors Considerations

Within the broad spectrum of Human Factors disciplines, Human Engineering is a particular discipline dealing solely with the man-machine interface. As applied to the MFDCS, such things as access schema, display design, keyboard/system dialogue, and man/computer function allocation are studied as a part of the overall human engineering study.

2.1.1 Automation vs. Manual Operation

One of the primary functions of a human engineering study is a function allocation analysis, i.e., determining which tasks should be allocated to the man and which tasks should be allocated to the computer. Important factors which govern this analysis are: 1) time required vs. time allowed, 2) error probability, and 3) task complexity.

Cohesive, accurate and rapid operator management of failures usually present the greatest human factor problems in complex systems. A case in point is the EPDCS in the Orbiter. If a main bus is lost, for example, the operators are now required to manually interface with many subsystems in the vehicle, whose controls are scattered throughout the flight deck. These procedures are currently contained on several pages of checklists and cue cards.

The requirement to perform a long list of sequential operator actions, addressing a multitude of subsystems, as found in the malfunction procedures for EPDCS, in itself creates a human factor problem with a MFDCS in that the operator must access each subsystem separately and key-in individual commands to each system element. Although switch locations are better localized for the OMS and EPDCS in the MFDCS, the number of key actions may exceed by a factor of 2 or 3 the number of switch actions required in the original system. The solution is to automate as much as possible the OMS and EPDCS functions involved in a given procedure.

However, when there is a probability that one or more steps might be purposely bypassed, each step must be monitored by the operator(s) as performed and only bypassed by deliberate operator action.

Even though a set of commands may be automated, good human engineering practice requires that the operator must have the capability to issue each command individually in a manual mode thus bypassing the automatic mode if desired. (Reference 2-1). To do this, he must be provided a sequential list of what tasks <u>should</u> be done and compare with what tasks <u>are</u> being done or <u>have</u> been done.

Exceptions to this rule are when the computations required are so complex, the timing of the action so precise, and the results of human error so drastic that the system commands are removed from human control and relegated to the computer. An example of this is the timing and gimbal control of the OMS I burn. Even in this case, however, the crew can override the General Purpose Computer (GPC) and inhibit the burn by either of two switch actions, but are not allowed to perform the computations to start the burn, terminate the burn, or manipulate the engine gimbals during the burn when following normal procedures.

2.1.2 Displays

Man becomes anxious when deprived of adequate information about what is going on about him. Man wants to see and hear as much as he can of the things that concern him. Consequently, even if not otherwise necessary, he should be provided with all information relevant to his job. (Reference 2-1).

This is not to say that the operators should be displayed all information all of the time. But when desired, he should be able to call up a subsystem situation display which contains all system parameters and trends. By the same token, if a set of anomaly response tasks are being performed automatically, he should be able to track and check off each task as it is performed. By using man in this way, as a monitor in the automatic or semi-automatic mode, he is better able to use his superior qualities of logical induction if catastrophic or massive failures of automation should occur.

There are two basic kinds of displays; symbolic and pictorial. In symbolic displays, the information presented has no pictorial resemblence to the conditions represented. Pictorial displays do have a pictorial, geometrical or schematic resemblence to the things they

represent. Pictorial displays are generally superior for showing relationships between things such as system flow schematics, and when properly designed, are more easily interpreted and require less training to use than purely symbolic indicators for the same functions. (Reference 2-2). Metered data can be portrayed as a dynamic inset on a pictorial display. An example is the use of analog meters displayed on the Boeing 757 CRT displays. Rate data may be included where necessary as a dynamic inset using a pictorial or alphanumeric format.

CRT displays in the current Orbiter are symbolic (in tabular form) for quantitative reading and require the operator to relate a number shown on the tabular display to an element located somewhere in the system. The location of that element and the effects of that element's status on the total system must now be either learned by the operator or found by reference to a paper schematic. In general, the use of purely tabular displays in a complex system environment is considered inferior to pictorial and/or combinations of pictorial/symbolic displays.

The question of whether to include color in a MFDCS visual display involves several issues. Color offers potential benefits by providing an additional dimension for encoding information. Color also imposes penalties in terms of display hardware cost, reliability, lower spatial resolution and possible clutter. The MFDCS concepts discussed in this document are not dependent on the use of color but most can benefit from the addition of color. Displays are coded to impart the information in monochrome or color. In this sense, color is a redundant enhancement of the displays.

Thousands of colors can be displayed on a shadow mask CRT but only a few are useful for encoding displayed data. The upper limit on the number of colors that can be used depends on several factors. The limit is much smaller if the observer must identify each color when it is present singly, rather than just distinguishing that two adjacent colors are different. The upper limit is also lower if a wide range of illumination conditions can occur. To cite one specific example, the seven colors on the avionics displays used in the new Boeing 757/767 aircraft (see Section 3.3) were selected to be identifiable on a vertical or horizontal situation display under display intensity settings and illumination conditions ranging from direct sunlight falling on the display to a light level commensurate to maintaining observer dark adaptation as required for night landings. (References 2-3 and 2-4).

Color can be used to encode information redundantly with some other dimension such as a symbol shape or nonredundantly. If the encoding is not redundant the observer must correctly identify the color to obtain the displayed information. If important information is involved, the designer must be certain that nothing will interfere with the display of color nor with the observer's ability to identify each displayed color. Redundant coding is most useful as an aid in locating particular elements or classes of information. For example, all the information on one topic in a large table might be a single color matching the remainder of the table. In this application, the display user could read each item in the table and eventually locate all the items on that topic, but these could be located if they were all a single color that differed from the rest of the table.

Excessive use of color, particularly by the introduction of too many different (more than seven, as determined on the 757-767 CRT design) colors, can increase the information density on a display and interfere with the interpretation of the displayed information. Experience in the design of color displays indicates that overuse of color is one of the most common faults that occurs.

2.1.3 Touch Panels

Touch panel technology has advanced to a point which makes them very attractive for certain applications. To be able to touch a display surface and cause desired actions to happen has certain human factors advantages, depending upon the application and the environment, despite the lack of tactile feedback. A stable environment such as a ground station or a stable platform, which would minimize inadvertant touching of the wrong controls is desirable for touch panel application.

The Orbiter missions pose certain problems to such an environment. The flight crew must operate in both a high G and zero G environment. In the latter, floating objects will require protection from inadvertent touch panel operation. This is evidenced by the fences currently built around the controls on the Orbiter center console to prevent accidental activation of controls during zero G.

Date entry and menu selections using touch panels will require consideration of the available touch panel resolution, the variety of operating conditions and the available panel space.

2.1.4 Cursor Positioning

Boeing has considerable experience with cursor positioning in command and control systems such as the E-3A. On the E-3A CRT displays, targets are designated by cursor positioning and "hooked". From that point on the computer interrogates and keeps track of that target and displays all relevent information about it, such as friend or foe.

Study of the current Orbiter mission revealed no particular advantages of cursor designation over keyboard noun designation since the application and mission dynamics are different. On one hand, fewer keys would be required and on the other cursor positioning "hooking" required more time and precision. Based upon the OMS and EPDCS study, cursor designation is not recommended at this time.

2.2 Hardware and Software Definition

The choices of hardware and/or software selected for application to the alternate MFDCS designs are constrained by a number of factors. Some of these factors are relevant to the Orbiter as a whole and others are a result of the scope and restrictions of the statement-of-work (SOW) for this contract. In a number of cases the possible design choices represent a trade-off between different advantages with each choice also having attendent disadvantages. A number of relevant factors considered in the alternate designs are discussed in the following subsections.

2.2.1 Weight

The advantage of reduced weight on the Orbiter is the potential for increased payload. Weight reduction is particularly important on the flight deck because of the requirement forcounterweighting in the rear of the vehicle to maintain an appropriate center of gravity. Weight savings can be produced if the MFDCS can be designed to weigh less than the current hardware plus the weight of the printed material incorporated into the MFDCS memory. If only the OMS and EPDCS system are included in the MFDCS and if hardware impact is minimized, then it will be difficult to save weight. Weight reductions using a more general MFDCS design could result in weight reductions through reduced wiring harnesses and support structure.

2.2.2 Power and Cooling

Power minimization results in a lower required electrical capacity and hence in a potential for reduced weight. At a minimum, the fuel for the fuel cells can be reduced at a weight savings of ~0.3kg/kwh. Similarly a lower power requirement will require less cooling and hence represent an additional weight and power reduction.

2.2.3 Volume, Panel Space and Physical Configuration

Volume and panel space are essentially predetermined by the Orbiter structure. A reduction of volume for displays and controls offers the possibility of using the space for another purpose. One of the study objectives constraints was that the designs developed have a minimum impact on the hardware configuration of the Orbiter. In previous discussions of potential physical layouts this requirement has been taken to mean that the OMS and EPDCS MFDCS must fit into the panel area and associated volume currently occupied by the present OMS and EPDCS hardware. Thus the primary area available is on panel R1. It should be noted that this requirement will increase by 1-3 the number of Orbiter displays for the design concept under study. In a general redesign of Orbiter displays and controls, the OMS and EPDCS displays could be integrated into the centralized displays on the front panel. Another area where minimum hardware impact enters the design is in the handling of circuit breakers. Currently, these are used, in effect, as switches in a variety of procedures. To avoid reconfiguring the electrical system, the circuit breakers must be left in place and operated by hand. Thus, certain steps in what could be an automatic operation will continue to require operator interaction. In a more general redesign, remote control and status monitoring of the circuit breakers could be used to save hardware and weight through reduction of wiring harness and manual access.

2.2.4 Software Impact Minimization

The current software package on the Orbiter is subject to a long lead time requirement for additions and modifications. In addition, the available memory for software associated with an MFDCS is very limited. As a result, the design alternatives developed in this report all assume that the MFDCS acts as a stand-alone processor with a communication link to the Orbiter General Purpose Computers (GPC's). In accordance with earlier discussions at NASA-JSC, the details of the link and the specific software structure for transmitting commands and receiving sensor data has not been specifically defined. A basic assumption

is the replication of the present EPDCS and OMS interface to the GPC's as closely as possible.

2.3 Specific Design Alternatives

There are several options available for implementing the design concept developed in Task 2. These options represent, in general, trade-offs between potential advantages to the Orbiter and/or crew from a particular MFDCS configuration. All the alternative designs assume a basic architecture as shown in Figure 2.3-1. The processor interacts with the GPC's via a communication link which provides the MFDCS processor with data and caution and warning alerts and permits the MFDCS to transmit command messages which simulate the interfaces previously used by the OMS and EPDCS switches. A high resolution display ($\geq$32 lines/cm) provides the capability for the display of schematic diagrams representing configuration and status of Orbiter systems. The medium resolution display (25-30 lines/cm) is used for the display of checklists, procedures and limited instrumentation or trend data. The multifunction keyboard provides the operator input mechanism for issuing commands to the GPC's and for manipulating the MFDCS displays. Dashed lines in Figure 2.3-1 indicate an interaction path which does not exist in all the design alternatives.

Initial formulations for the displays and access schema for operation of this type of system were presented at the Task 2 review. Revisions were made as a result of these discussions and a second version was reviewed at length during a visit to Boeing by John Creighton (NASA-JSC). The current set of features and the access schema is an outgrowth of these reviews and discussions. Basically, the system is designed to operate in four major modes. These modes are common to the various specific designs presented.

The first mode covers normal operation of the systems and presents the crew with an overall display of system status and the keyboard entry options necessary to access the OMS or EPDCS in more detail. Display of system status is an option selectable by the operator. A basic feature of the system is the display of only that information necessary to or desired by the operator.

A second mode provides operator access to the normal operations of the system, to checklist presentation and to certain predefined operations associated with OMS and/or EPDCS malfunctions. In this mode, the operator has the choice of selecting automatic or semi-automatic completion of the procedure configuration or checklist in question.

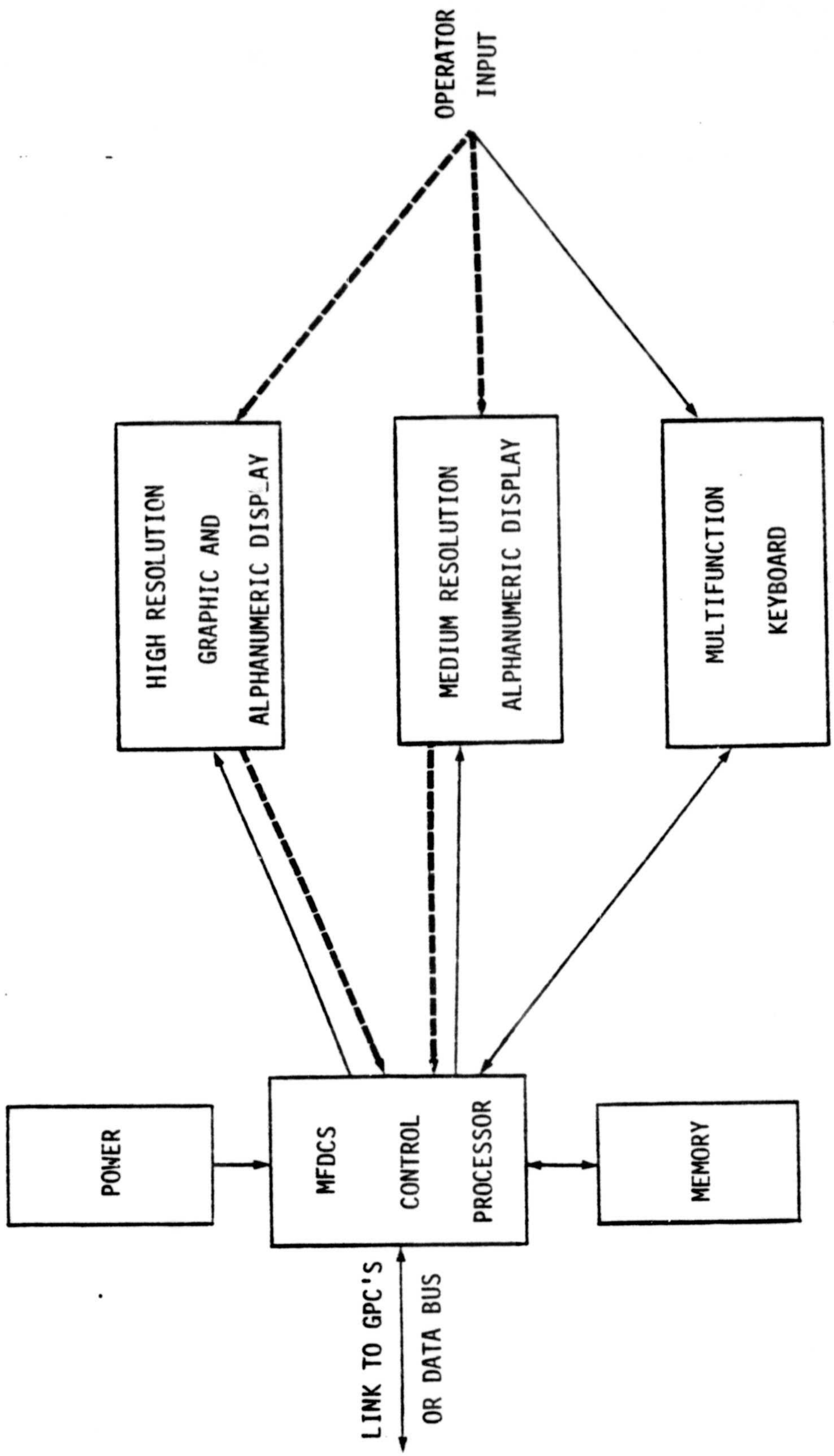

FIGURE 2.3-1 MFDCS BASIC ARCHITECTURE

Fault detection, alerts and warnings are handled by the third mode. Incoming fault messages are prioritized in terms of probable system impact and displayed to the operator. The operator may then select which, if any, of the faults he wishes to deal with. Selection of a fault to deal with also provides the operator with a suggested procedure, if available, for dealing with the problem. Here too, the operator has the option of performing all or part of the procedure and, if performing all, of doing so in an automatic or semi-automatic mode. The choices between automatic, semi-automatic or partial procedure implementation preserve the command supervision capability of the crew while providing the capability for automation during conditions of heavy workload.

The fourth mode of operation is similar to the system currently available on the Orbiter in that it provides access to the individual switch and control functions within the system. In addition, this phase includes the most detailed displays of the subsystems within the OMS and EPDCS. Although very comprehensive, this mode is more time consuming to operate within than are the other modes. As a result it is envisioned primarily for use in a diagnostic or trouble-shooting mode during periods when the crew has more time to work on problem solutions.

The design alternatives for the MFDCS can be broken down into several basic areas. These include the host-MFDCS interface, MFDCS processing architecture, processor-Keyboard/display interface, MFDCS displays and the logic structure and access schema design. The following subsections describe some of the design options associated with the hardware and software in the system. These options are considered in more detail in Section 3.4 where the correlation between system requirements and projected design performance are evaluated and in Section 4 where the results of the feasibility testing are presented.

2.3.1 Host-MFDCS Interface

Multifunction display and control system have been constructed with a variety of division points between host functions and those of the MFDCS. In the Orbiter, however, the limited host memory and the requirement for minimal software impact by the MFDCS requires that the MFDCS rely on the host GPC's for only the transmission of commands to, and reception of data from, the host. Essentially, the MFDCS must simulate the present interface of the OMS switches to the GPC's. The EPDCS contains numerous switches which do not pass through the GPC's. The MFDCS will be required to contain a set of drivers to activate switches of the EPDCS under microprocessor control. It has been assumed that sensor data needed by the MFDCS will be available by tieing the MFDCS into the Orbiter data bus.

2.3.2 MFDCS Processing Architecture

The architecture selected for the MFDCS controller processor (and associated memory) will depend heavily on the required display storage capacity and data base complexity. Both 16 and 8 bit microprocessors were surveyed for use as the central MFDCS processor. In addition, estimates were made of the required memory capacity for data base and medium resolution display storage. High resolution display storage will depend on the types and number of displays selected. This selection will define the potential need for a mass storage memory device.

2.3.3 Processor - Keyboard/Display Interface

Either serial or parallel interfacing can be used to link the displays and keyboard to the MFDCS controller. Both were considered as design options for the MFDCS. Also considered was the need for distributed processors as a function of the display varieties chosen.

2.3.4 MFDCS Displays and Controls

A number of display options were considered for the MFDCS. Within the constraint of available panel space major options include: 1) the use of a single large CRT display for high resolution, checklist display and keyboard portrayal, 2) a separate CRT display for high resolution and flat panel displays for checklist and keyboard portrayal, and 3) a separate CRT display for high resolution, flat panel display for checklists and an array of individual multifunction switches forming a keyboard. In option 1) and 2) the operator would control the system via touch panels over the displays or using bezel edit switches on the display perimeters. In option 3) the multifunction switch array would provide operator control of the MFDCS. These options are analyzed in Section 3.

2.3.5 Logic Structure and Access Schema Design

The form of the logic structure and access schema for the MFDCS has been discussed at some length in the Task 2 reviews and during visits to Boeing by NASA-JSC personnel. The general form and functions included are results of those discussions and the work under Task 3. A final design requires a great deal of coordination between the choice of display diagrams, procedures and checklists, and the keyboard legends. The scheme portrayed in Section 3 operates in four major modes as described earlier. A major feature of the design

is a high degree of flexibility allowing a straightforward method of changing logic tree branching, legend, checklist and display presentation in the data base to coordinate with mission or hardware changes.

3.0 Design Analysis

This section of the report describes the conditions and requirements assumed in the analysis of the specific OMS and EPDCS MFDCS designs. In addition the correlation of design features with system requirements and the degree of design conformance to human factors considerations are described. The design analysis leads to the definition of required feasibility testing. Section 3.1 gives a brief description of Orbiter operating conditions.

3.1 Orbiter Operating Conditions

The Orbiter operating conditions can be divided into three major phases. The first is the time period from launch to the achievement of a nominal orbital status at the conclusion of the second OMS burn. On orbit operation prior to the re-entry OMS burn is a second phase. The third phase includes the time from the OMS re-entry burn to the conclusion of landing activities. All three phases are subject to degraded operating conditions caused by environmental or internal system factors. Conditions assumed in the specific designs are described in the following two subsections. The desirability of reducing weight, power and cooling requirements is assumed for all operating conditions.

3.1.1 Launch to Orbit

Under normal operating conditions the primary constraints on the Orbiter crew will be the acceleration and vibration associated with launch and the limited time within which the two OMS burns must be completed. This phase will also include periods of weightlessness. A shirt sleeve operating environment is assumed.

Degraded operating conditions during this phase include the various abort modes due to system failure, propulsion malfunction or environmental hazard such as fire or loss of cabin pressure. A major result of any problems during this phase of operation is a reduction in time available to perform the necessary tasks and a considerable increase in risk to the crew and vehicle. Actions taken to correct system faults during this phase are, in general, limited to those necessary to safe the system and continue with necessary operations. The procedures to be followed are generally defined as requiring less than five minutes to perform and are included in the pocket checklists and/or cue cards.

3.1.2 On Orbit

During an orbit operation, a shirt sleeve environment remains normal. With the exception of planned OMS or RCS burns, zero gravity conditions prevail during this phase of the mission. Time constraints will be determined primarily by operation of equipment to complete mission objectives as opposed to actions necessary to achieve vehicle safety. Systems such as the OMS and EPDCS will normally require relatively little operator interaction and the interaction necessary can be planned in advance.

Degraded operation during this phase of the mission include any elements of Orbiter system or payload failure as well as environmental hazards. Time is potentially both a positive and negative factor in this phase. The long (relative to launch or re-entry) duration of the on orbit phase provides time to safe the system and also to troubleshoot and/or work around the difficulty. On the other hand, it may not be possible to achieve a rapid return to a landing site if the problem represents an immediate unresolvable safety hazard. As an example an extended period of operation in space suits might be required under conditions of a severe pressure loss.

3.1.3 Re-entry

Normal re-entry depends initially on the success of the OMS re-entry burn. As the descent progresses, the major stress factors on the vehicle and/or crew are aerodynamic heating, a return to normal gravity, temporary loss of ground communication and a heavy workload associated with flight control and approach navigation. Once again, time becomes severely limited. A number of systems complete their function during this portion of the mission. Included in these systems are the OMS and RCS. In addition, systems not previously used, such as flight controls and air data, must operate in a normal fashion.

System failure or environmental hazards occurring after the OMS re-entry burn have a major effect on the workload of the crew because of the time constraints associated with making the re-entry flight maneuvers, maintaining vehicle altitude, monitoring systems and navigation equipment and communicating with the ground. In some cases, a system problem can be ignored if the time during which it will be used is short (e.g. FC coolant pump loss).

3.2 Orbiter System Functions

In order to determine the multifunction display/control requirements of the OMS and EPDCS it was necessary to tabulate the current displays/controls and understand their functions.

This ensured that all current display/control functions would be incorporated in the MFDCS concept as a minimum requirement. This tabulation is shown in Appendix A.

3.3 Human Factors Analysis

Within the framework of this study, the Electrical Power Distribution and Control System (EPDCS) and the Orbital Maneuvering System (OMS) have been examined in detail for their application to the MFDCS concept. The system functions of these two systems are shown in Appendix A of this document and were used as the basis for the Human Factor Analyses. Although only the EPDCS and OMS were analyzed, the access schema, functional organization and display concepts were evolved with an eye towards the impact on a total Orbiter MFDCS. Section 3.3.2 reviews many of the features important to achieving an effective display interface.

3.3.1 Functional Organization and Logic Design

A MFDCS can be configured in several different ways. In one approach every individual valve and relay in the system is available through some sequence of control actions by the operator. As an alternative approach, the operator selects operating modes each of which implies a particular set of valve or relay settings. The first approach is illustrated for an OMS MFDCS using the Figure 3.3.2-25 keyboard (located in Secton 3.3.2) with a L-R crossfeed (Figure 3.3.2-6 schematic) and the second using the 3.3.2-26 keyboard. It is important to note that these differing approaches depend much more on the software than the hardware used in the MFDCS.

The first approach, providing operator access to each individual valve and relay, does not improve the workload situation except under special circumstances. For example, in most cases a single operator control action is required to open a single OMS valve with the present dedicated controls, but with many MFDCS schemes this would require a sequence of several switch actions. This increase in number of control actions can be justified on the basis of workload only if the alternative is so many individual controls that some of them are out of the operator's reach, or if they are so scattered that they are difficult to learn.

If the major operating modes of a system can be defined, then implementation of these in the MFDCS will serve to reduce operator workload. Referring to the keyboard in Figure

3.3.2-26, for example, the operator having already selected Item 3 from the OMS Menu can accomplish this reconfiguration (a L-R X FEED OMS BURN) with only two control actions (AUTO MODE and EXEC) that will define and change the setting of 16 valves. In addition to reducing the number of control acitons, the operator is now able to interact with the system in terms of a goal (setting up for a particular type of OMS burn) without having to recall and perform a long series of control actions to reach that goal. However, the manual mode is still available if the operator desires to use it..

The major limitation of the second approach is that each operating mode must be identified and defined far enough prior to a mission to be implemented in the system software. Depending on the system this may be anyware from a few hours to several years. To allow for unforeseen situations, it is therefore essential that the operator also be able to access each individual valve and relay by placing the MFDCS in a backup and essentially manual mode.

An important human factor goal throughout the analyses was to develop an access schema which would allow access to the desired subsystem with the minimum number of operator key actions and look-ups. Therefore, it was decided that any correctable keystrokes which changed the display, but did not cause changes in the system, would not require the use of the EXECUTE key. This allows the operator to access any element of any subsystem, including checklists, schematics, together with an interactive keyboards, in two to three keystrokes as follows:

			RESULT	
FUNCTION	KEYBOARD	NO. KEYSTROKES	FLAT PANEL	CRT
Select Subsystem	Subsystem	1		Subsystem Menu
Select Segment or mode from menu	Numeric	1 or 2	Interactive Checklist*	Interactive Schematic*

*Plus Keyboard

Now the operator is ready to conduct a dialogue with the subsystem or subsystem elements, which may consist of one switch or valve change, or, a major reconfiguring of the subsystem. At this point, the operator must verify the command from the displayed "echo" and then strike the EXECUTE switch. A discussion of the interactions of the keyboard, checklist displays and schematic displays is contained in Section 3.3.2 of this document.

Throughout the analyses it became apparent that no hard and fast rule could be established with regard to keyboard/schematic manual dialogue at the interactive level during anomaly responses. Whereas it is appropriate to reconfigure the OMS values from a checklist and schematic, (either automatically or manually), in response to an OMS ENGINE LOST, for example, manual keyboard manipulation of switches using a schematic would be inappropriate and inefficient when responding to a MAIN BUS LOST for the EPDCS.

The latter checklist requires the operator to sequentially address many subsystems other than the EPDCS. The use of multifunction keyboard commands in this case requires too many keystrokes. Instead, several pages of checklist commands will be sequentially displayed in the flat panel display and automatically performed in groups as discussed in Section 3.3.2.

3.3.2 Concept Display and Control Modes

The proposed MFDCS concept incorporates a variety of graphical and programmable keyboard formats. These are described in detail below, first for the OMS and then for the EPDCS. Although color coding is not essential to the proposed MFDCS, it is useful and it has therefore been included in this description of the concept.

Two types of display formats will be required: 1) System Status and 2) Anomaly Responses. Each will have its own interactive keyboard, even though commonality of nomenclature and/or command mnemonics allows the same display or keyboard to be used for two or more different display/controls in some areas. This is particularly true of the OMS.

System Status Displays - As the name indicates, these are subsystem "Situation Displays" which display to the operator the position of every switch or valve in the subsystem segment displayed. Every switch or valve on that display can be changed by manual operation of the interactive keyboard. In addition, by operator request, system parameters such as pressure, temperature, quantity, etc., are displayed next to the relevant system element. If not in the

PARAMETER DISPLAY mode, any out-of-limit parameter will be automatically displayed in yellow or orange. This mode does not normally require a checklist display.

Anomaly Response Displays - Responses to anomalies are called up by operator menu selection and in some cases displayed automatically. Checklist and cue card information is displayed in the flat panel display accompanied by an interactive keyboard and in some cases an interactive schematic.

The schematic display reflects the true status of the subsystem segment and flags discrepancies between the true status and the desired status indicated by the anomaly checklist.

The desired status may be achieved in two ways, i.e., MANUAL or AUTO. In the MANUAL mode, the operator checks off each task sequentially as he follows the checklist.

In the AUTO mode the computer sequentially performs each task of the displayed checklist, placing a check mark by each completed task when checked off by the operator. Should the operator choose to skip any task he may do so by pressing the SKIP key and the remaining tasks will continue to be performed.

Orbital Maneuvering System - An OMS schematic has been developed which can be used for the modes listed in the OMS menu below. Valve positions and flow paths will be shown on the schematic based upon the mode requested. Checklist and cue card information will be displayed with the schematic in anomaly modes.

1. SYSTEM STATUS - ENGINE AND PROPELLANT
2. LEFT ENG. LOST - NORMAL FEED
3. LEFT ENG. LOST - L-R X FEED
4. LEFT ENG. LOST - MIXED FEED - L OX R FU
5. LEFT ENG. LOST - MIXED FEED - R OX L FU
6. RIGHT ENG. LOST - NORMAL FEED
7. RIGHT ENG. LOST - R-L X FEED
8. RIGHT ENG. LOST - MIXED FEED - L OX R FU
9. RIGHT ENG. LOST - MIXED FEED - R OX L FU
10. FU and OX TANK PRESSURE HIGH
11. N_2 TANK PRESSURE LOW

TEXT CONTINUED ON PAGE 48.

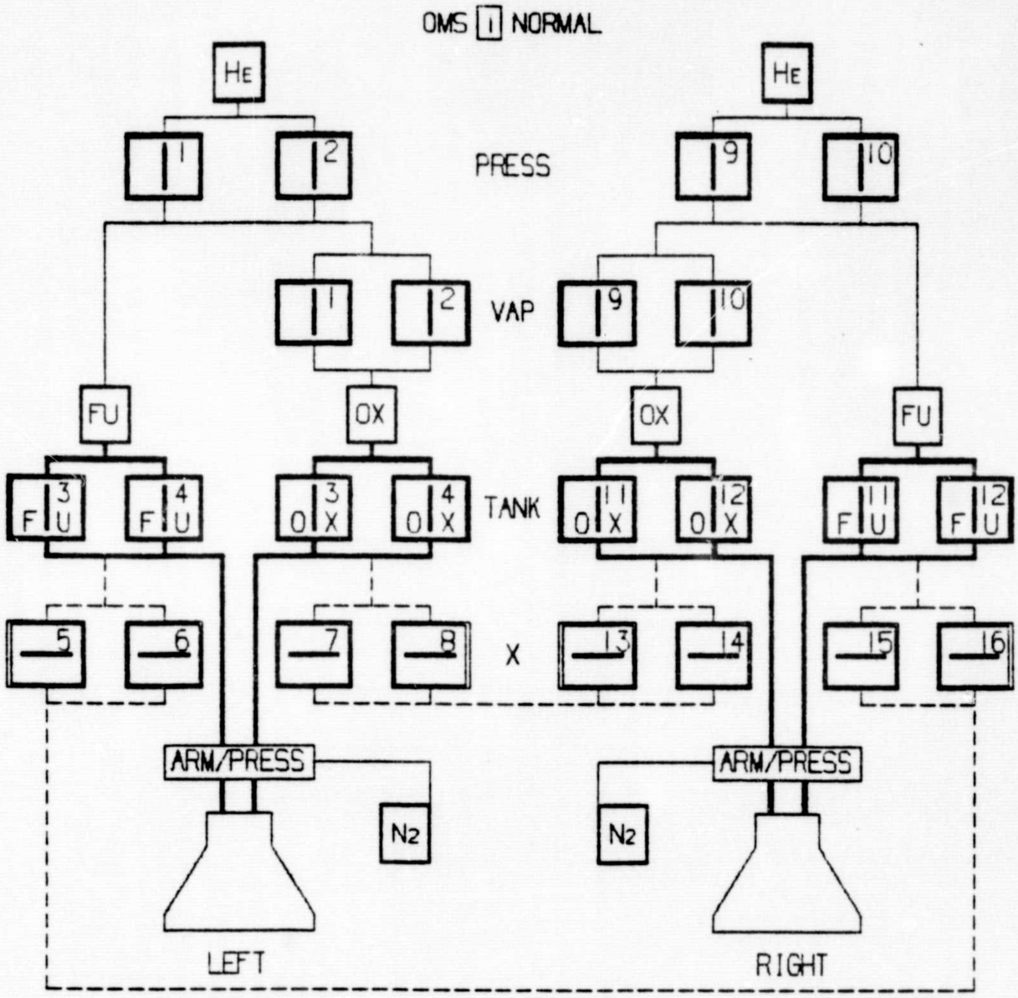

Figure 3.3.2-1 OMS VALVE STATUS DISPLAY - NORMAL

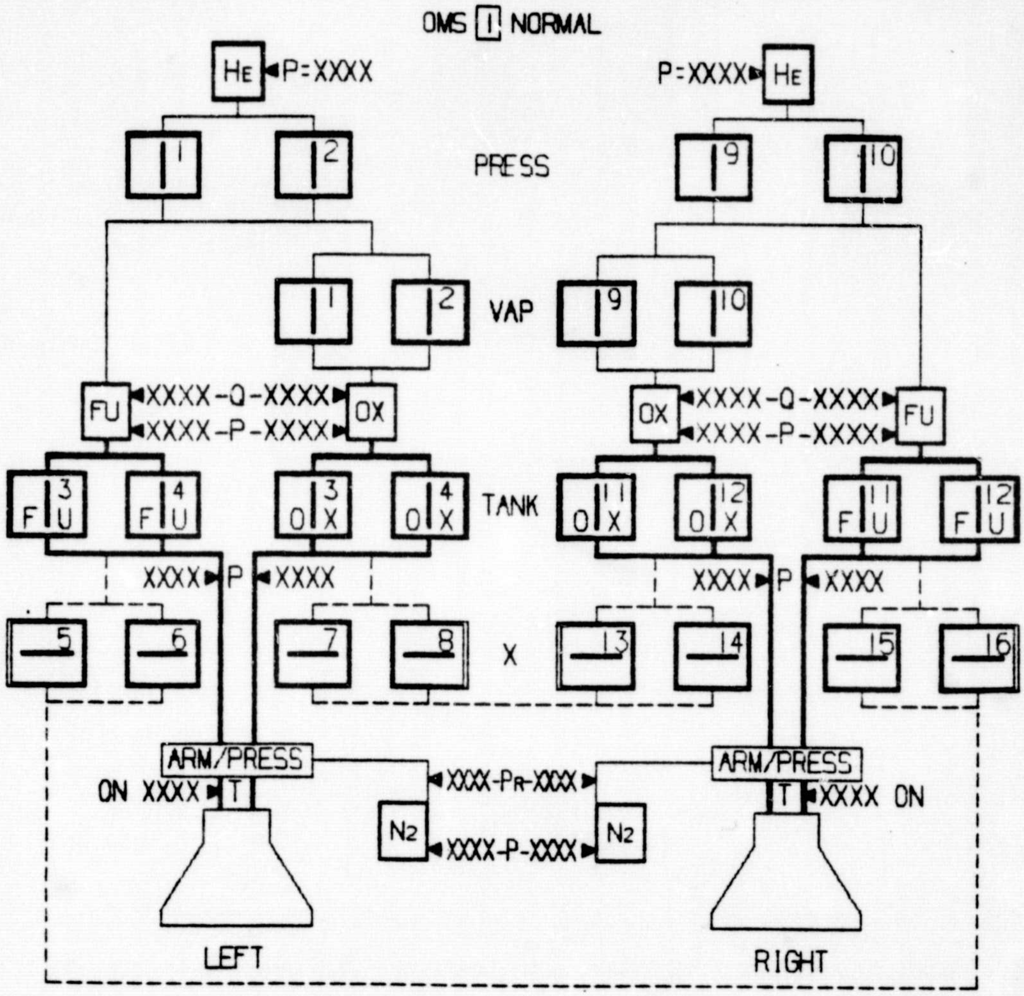

Figure 3.3.2-2 OMS VALVE & SYSTEM PARAMETER DISPLAY - NORMAL

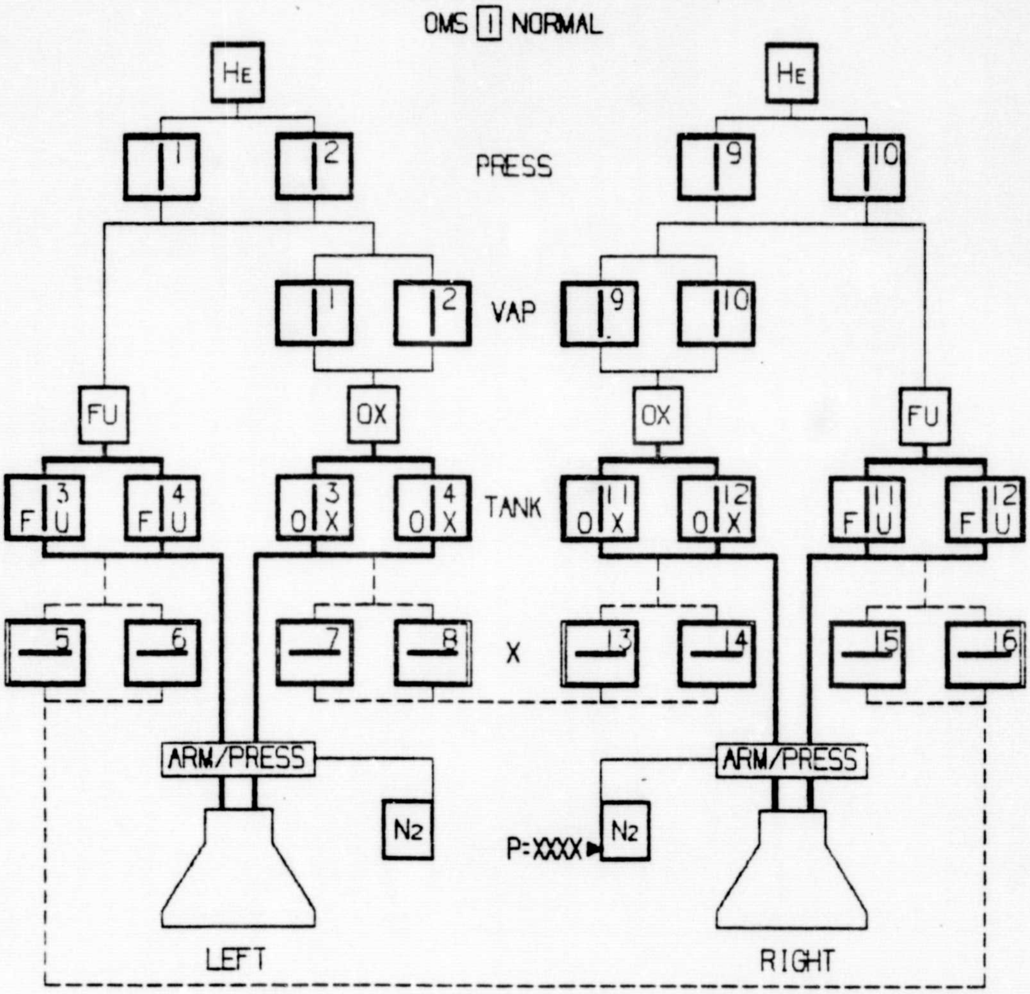

Figure 3.3.2-3 OMS VALVE STATUS DISPLAY SHOWING AUTOMATIC DISPLAY OF OUT-OF-LIMITS N_2 PRESSURE

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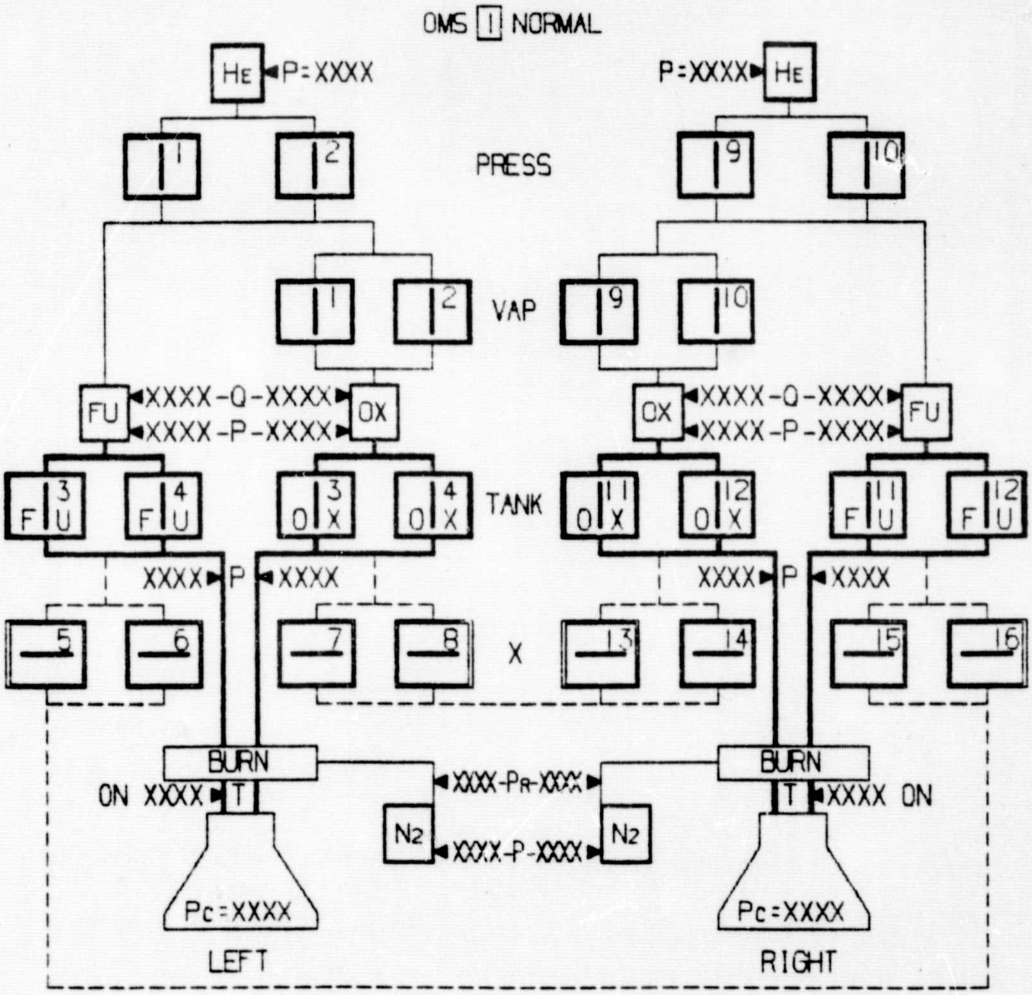

Figure 3.3.2-4 OMS TOTAL SYSTEM DISPLAY DURING BURN - NORMAL

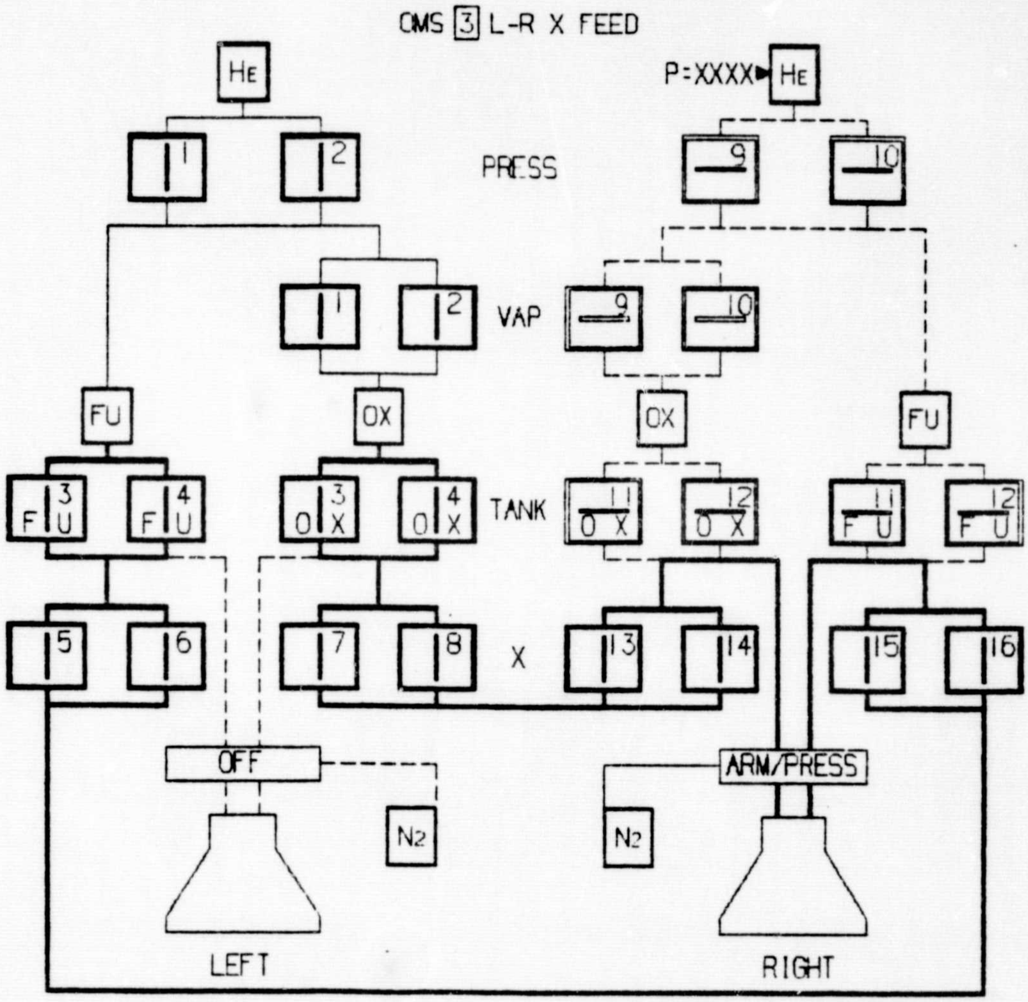

Figure 3.3.2-5 OMS VALVE STATUS DISPLAY FOR L-R XFEED. VALVES MAY BE MANUALLY CONFIGURED FROM MANUAL KEYBOARD OR AUTOMATICALLY CONFIGURED USING AUTO KEYBOARD.

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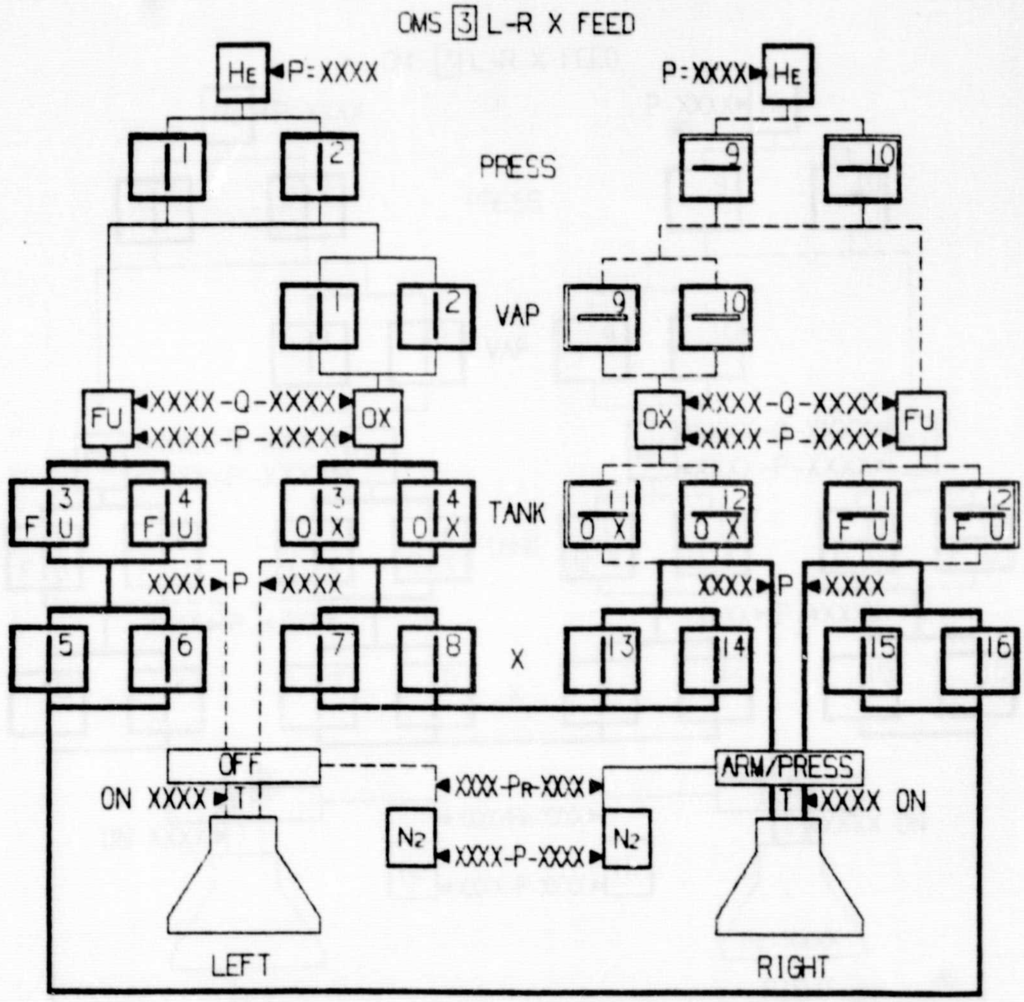

Figure 3.3.2-6 OMS VALVE & SYSTEM PARAMTER DISPLAY - L-R XFEED

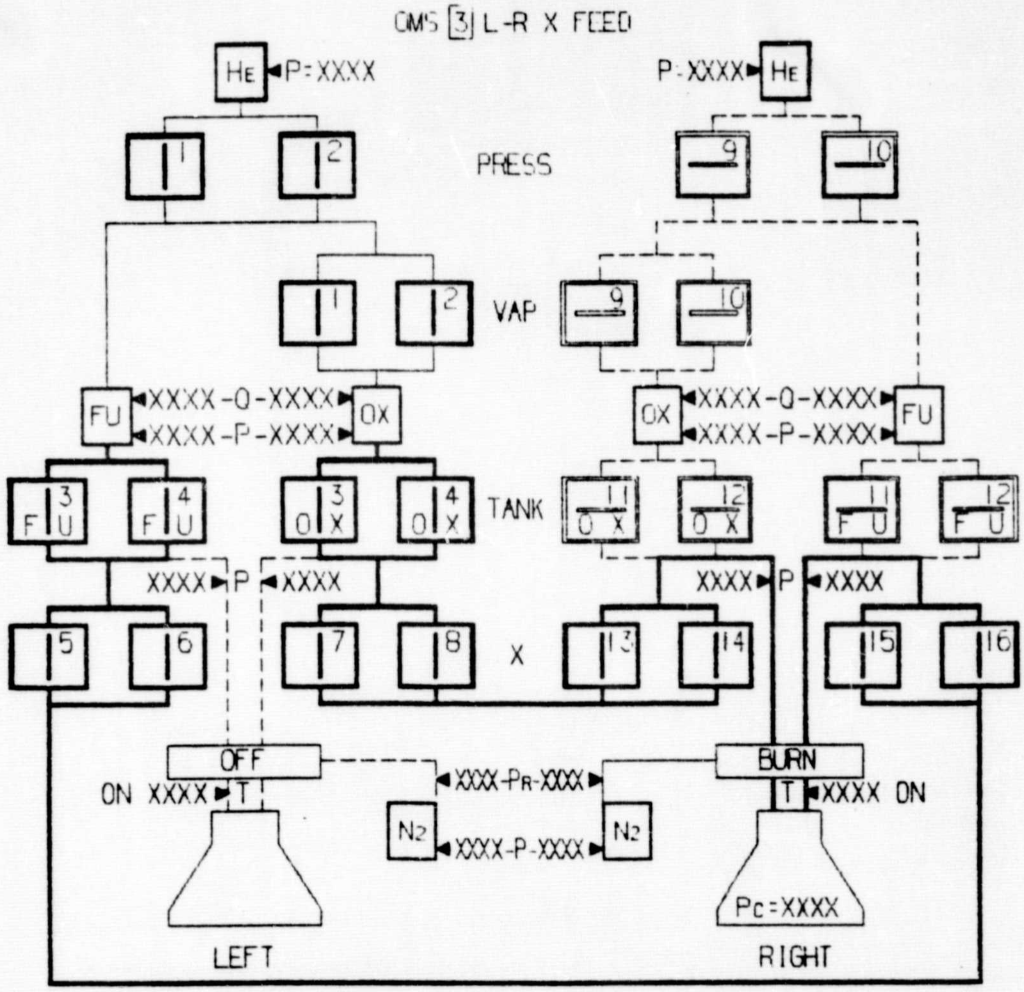

Figure 3.3.2-7 OMS TOTAL SYSTEM STATUS DURING BURN - L-R XFEED

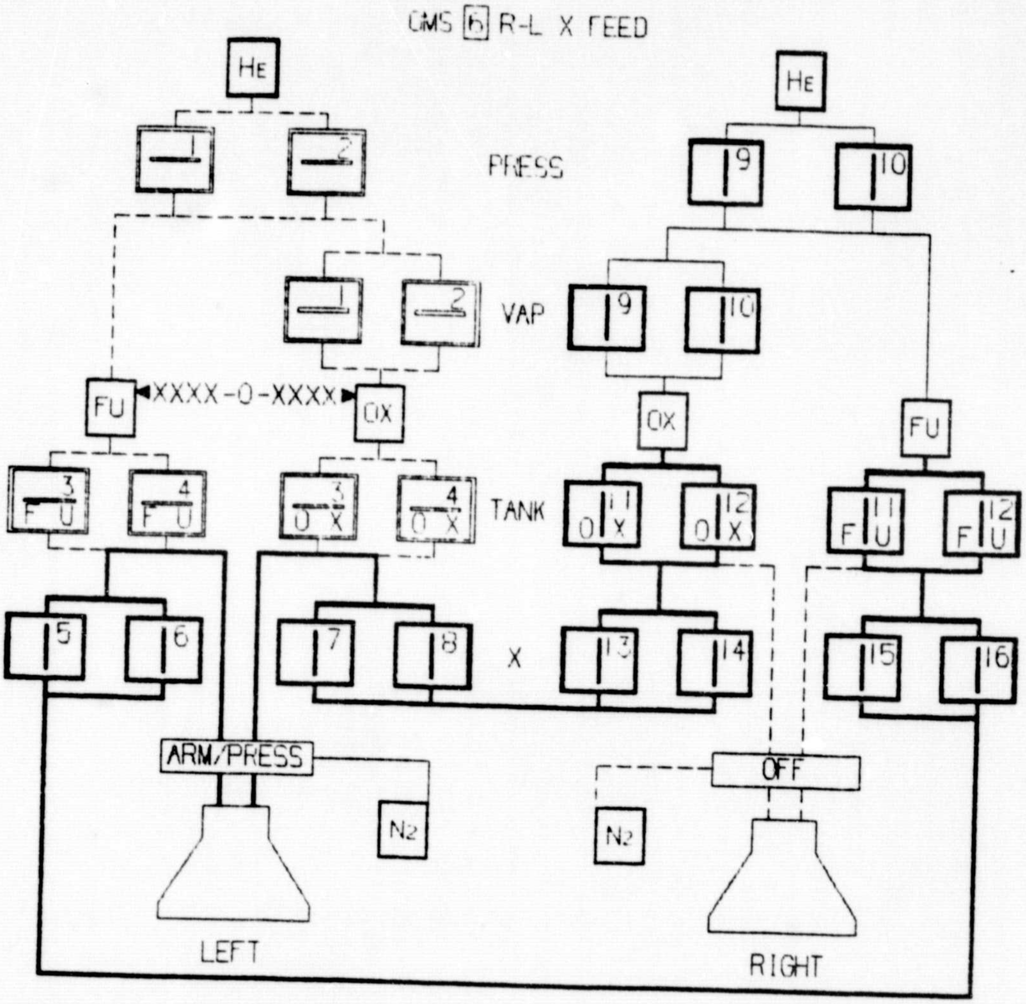

Figure 3.3.2-8 OMS VALVE STATUS DISPLAY FOR R-L XFEED SHOWING AUTOMATIC DISPLAY OF LOW FU & OX QUANITY

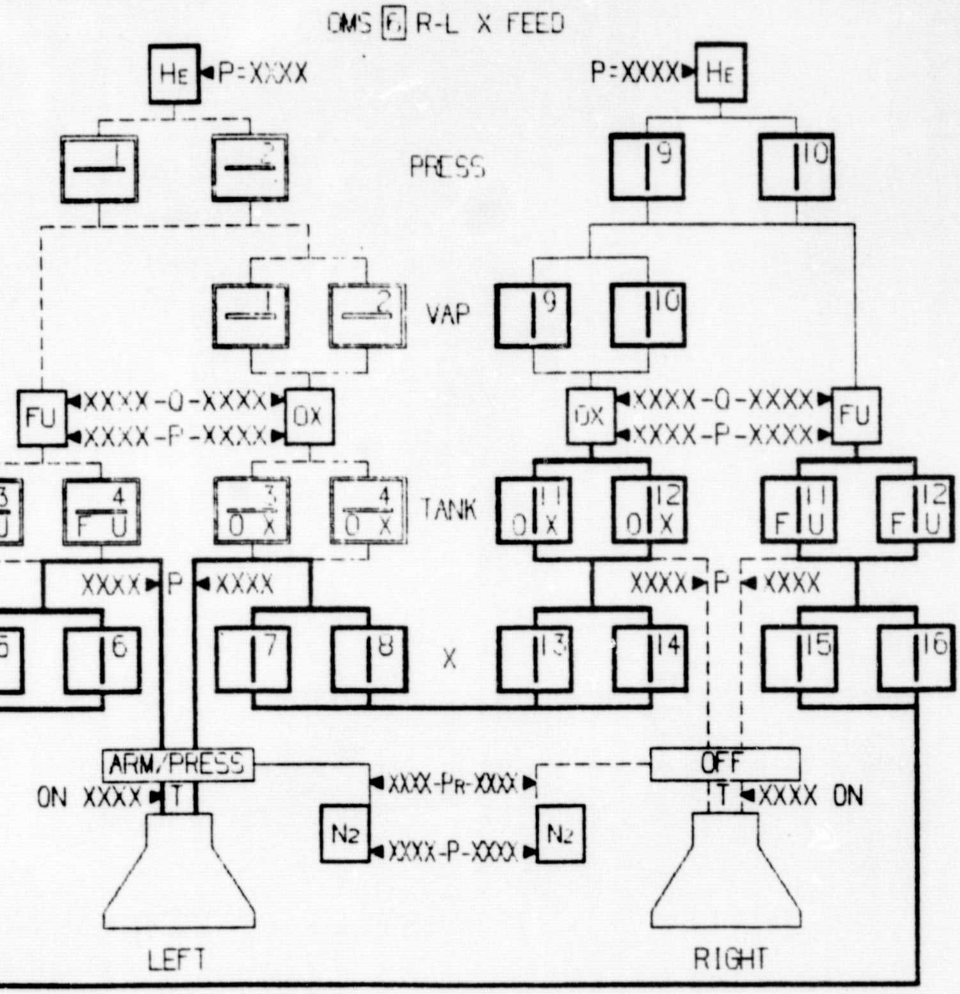

Figure 3.3.2-9 OMS VALVE & SYSTEM PARAMETER DISPLAY - R-L XFEED

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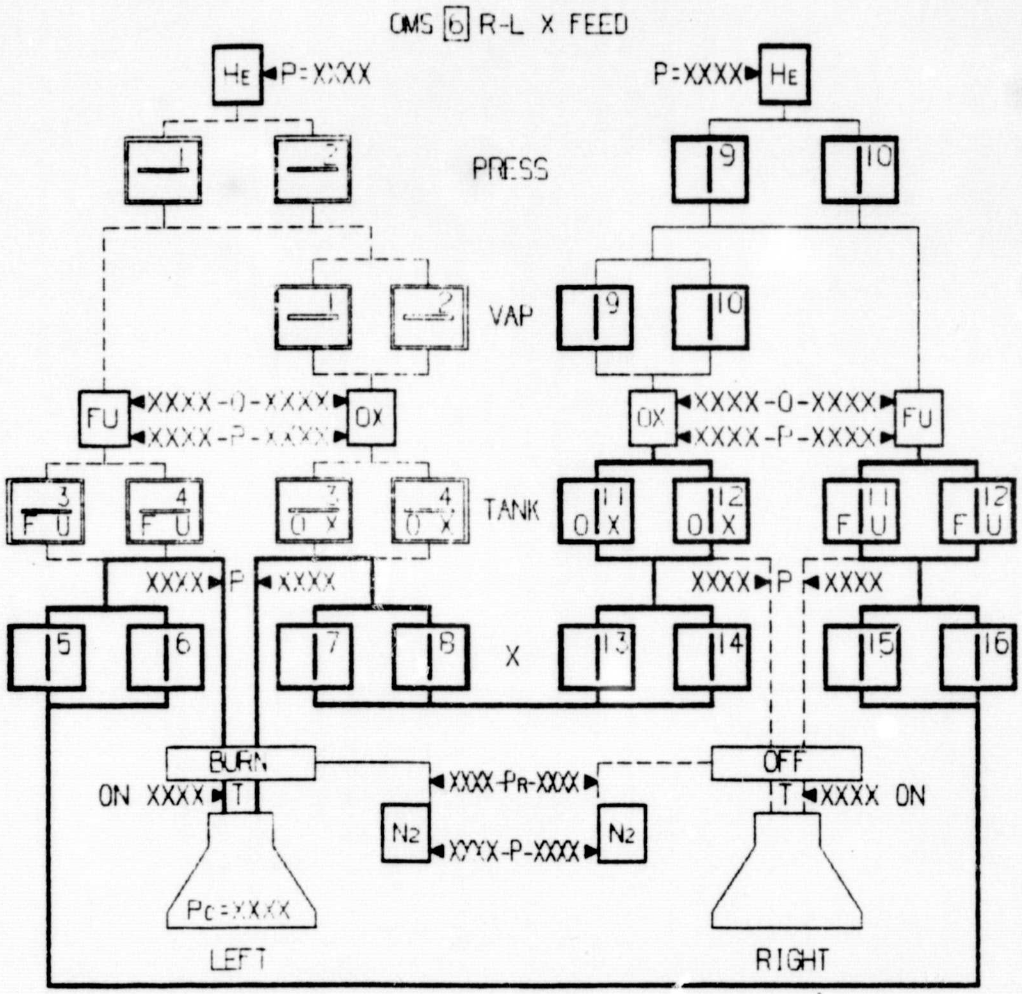

Figure 3.3.2-10 OMS TOTAL SYSTEM DISPLAY DURING BURN - R-L XFEED

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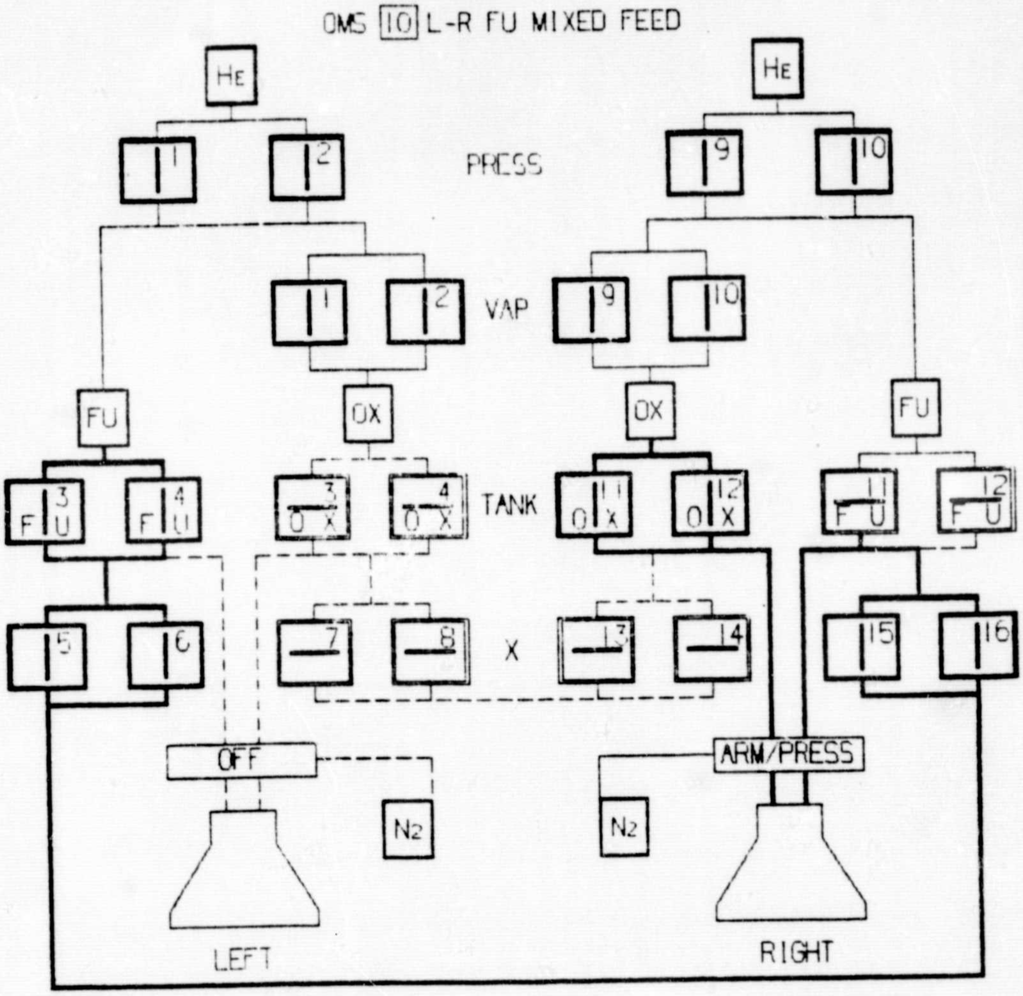

Figure 3.3.2-11 OMS VALVE STATUS DISPLAY - L-R FU MIXED FEED

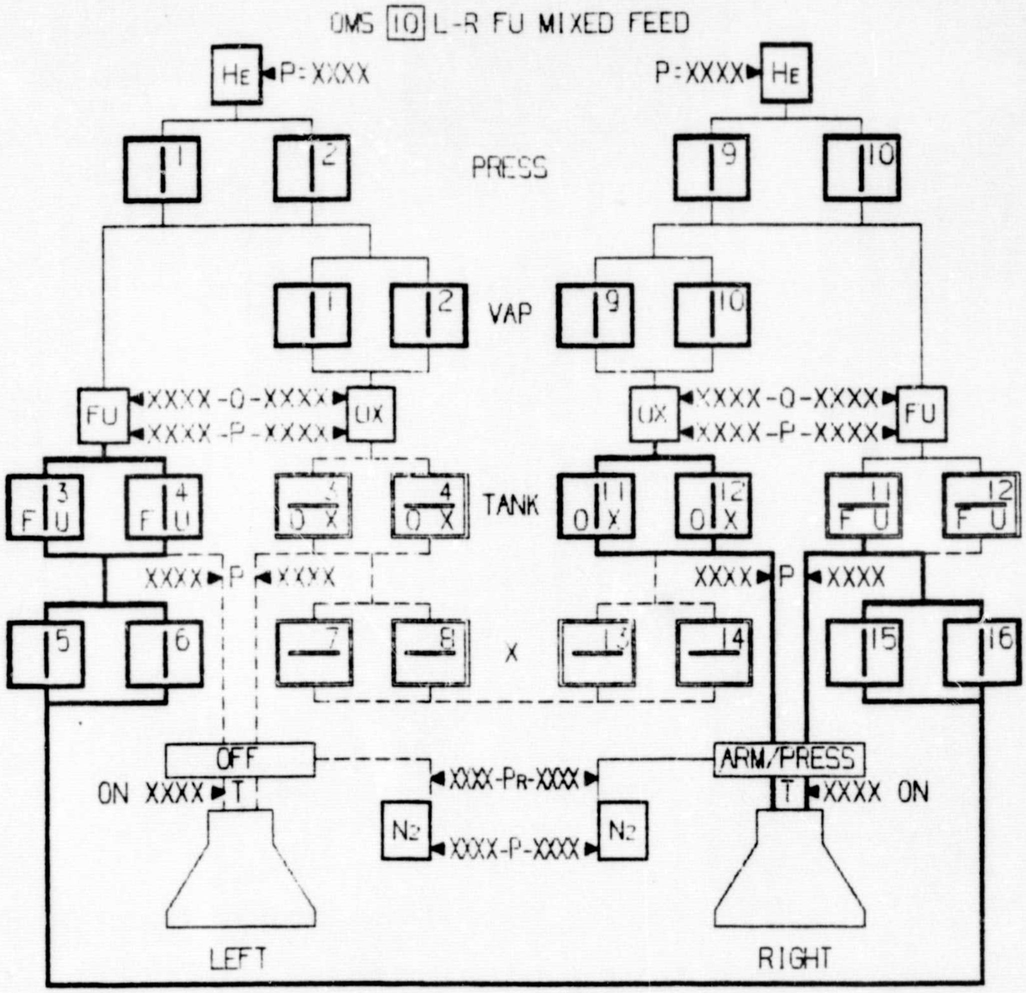

Figure 3.3.2-12 OMS VALVE & SYSTEM PARAMETER DISPLAY - L-R FU MIXED FEED

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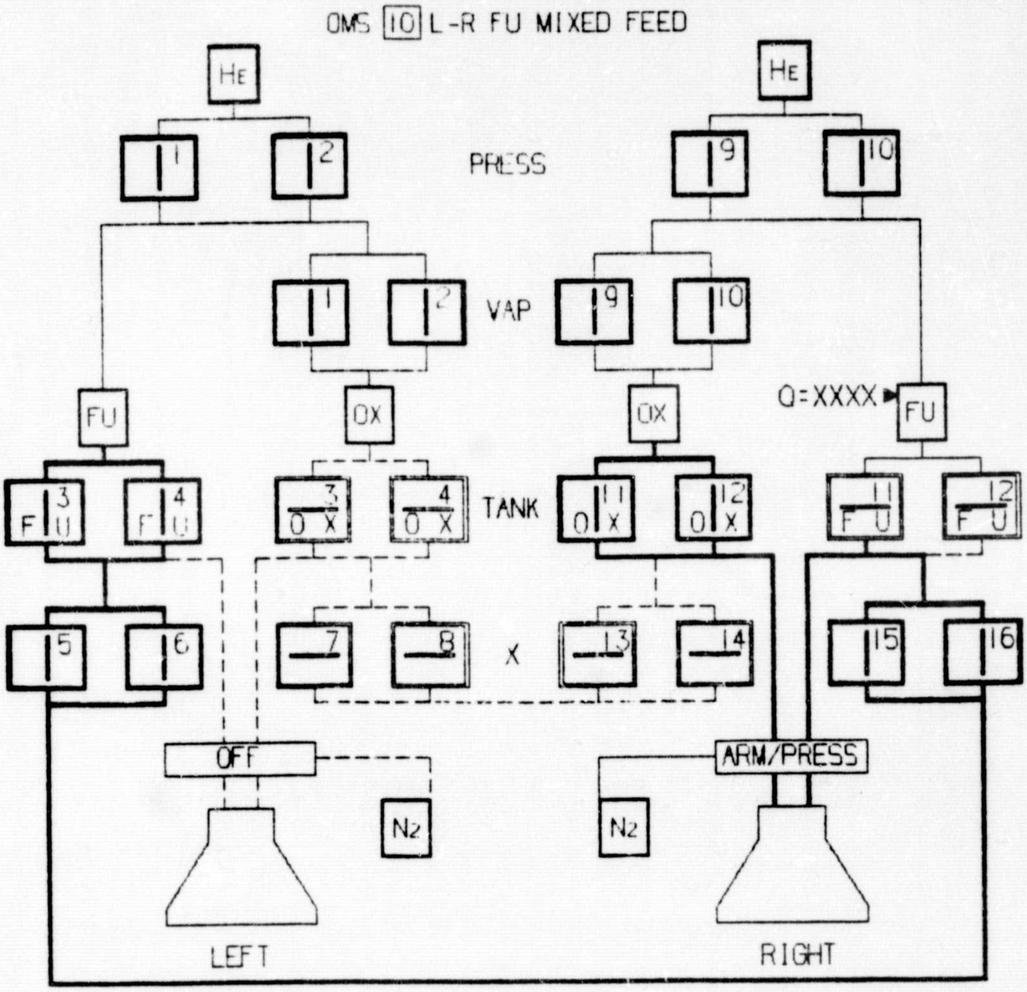

Figure 3.3.2-13 **OMS VALVE STATUS DISPLAY SHOWING AUTOMATIC DIPSLAY OF LOW FU QUANITY**

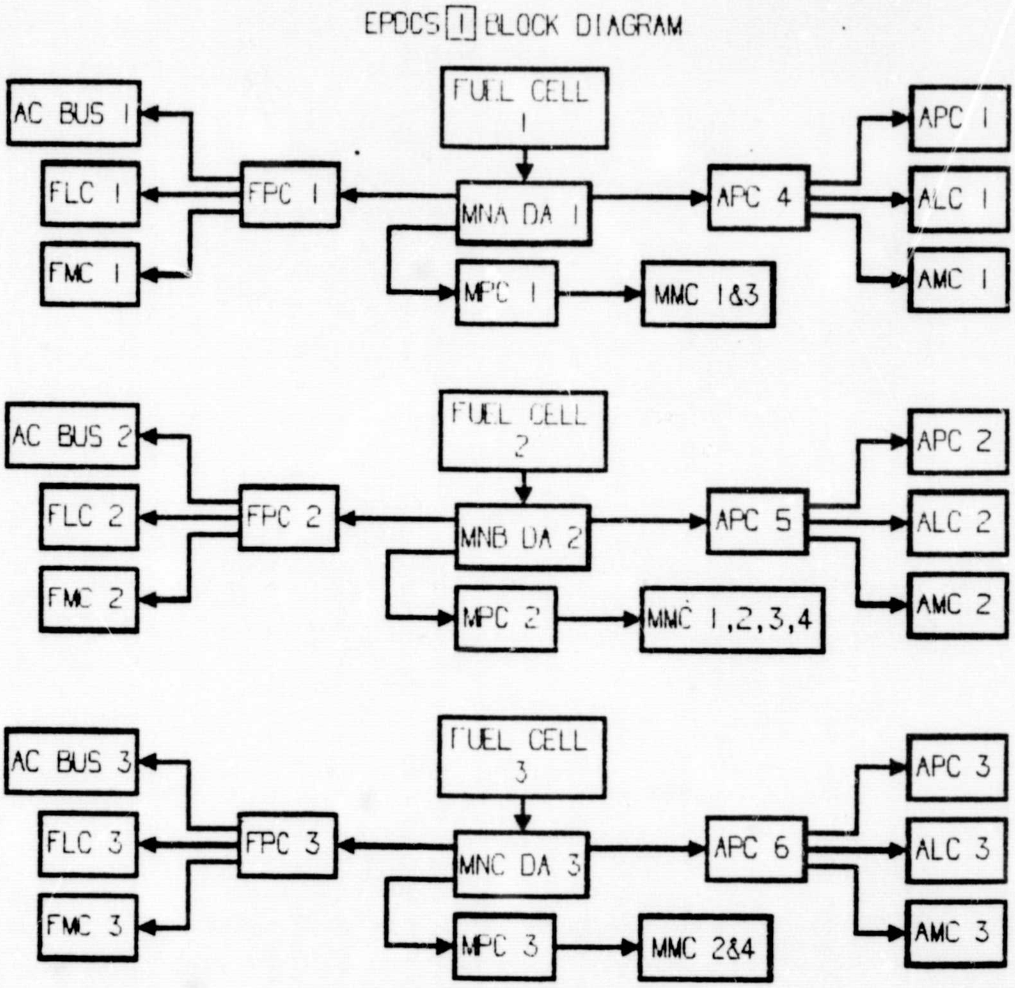

Figure 3.3.2-14 EPDCS BLOCK DIAGRAM DISPLAY

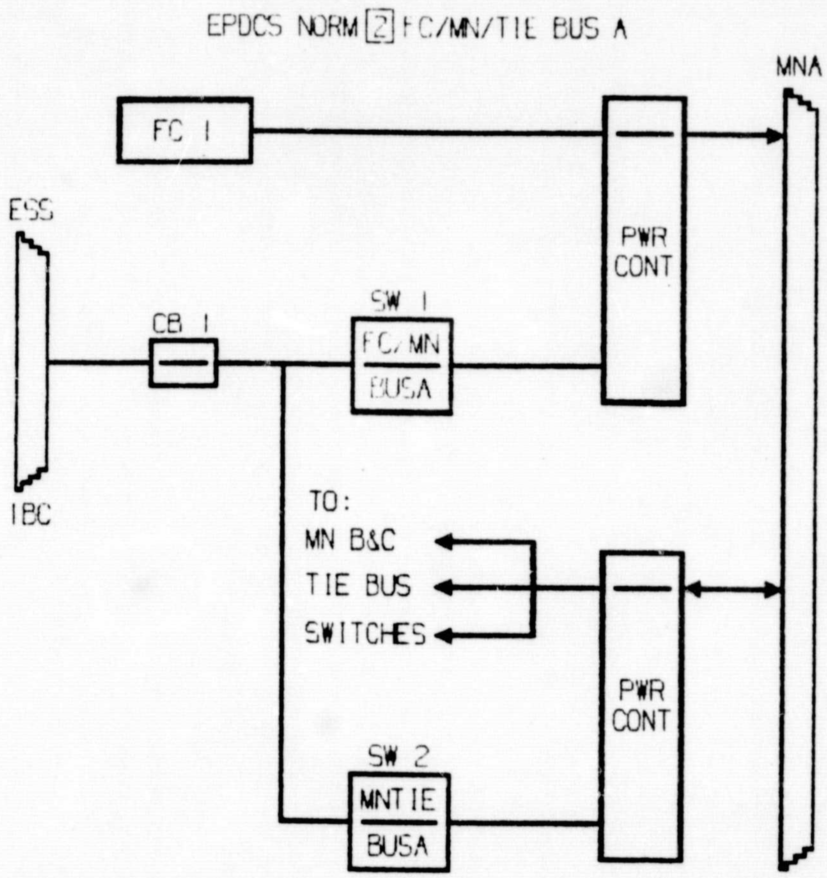

Figure 3.3.2-15 EPDCS FC/MN/TIE BUS A DISPLAY

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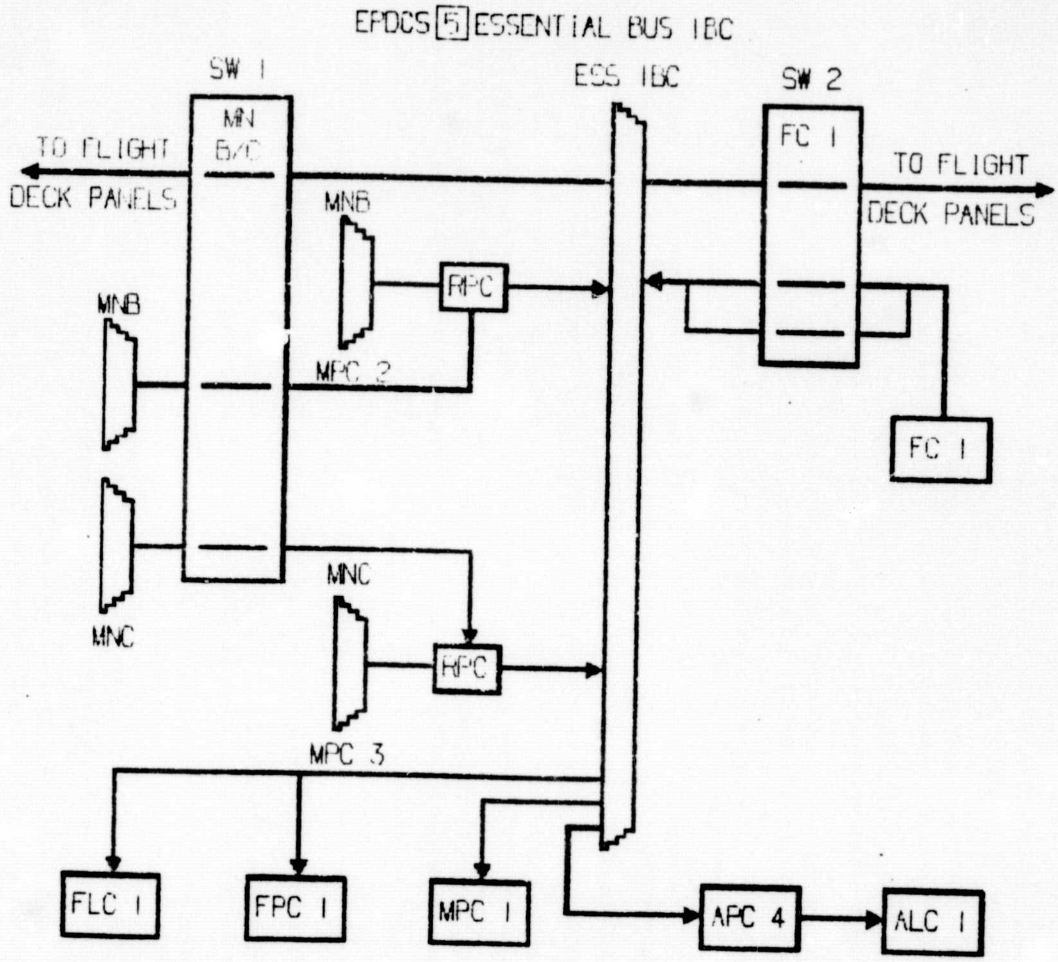

Figure 3.3.2-16 EPDCS ESSENTIAL BUS IBC DISPLAY

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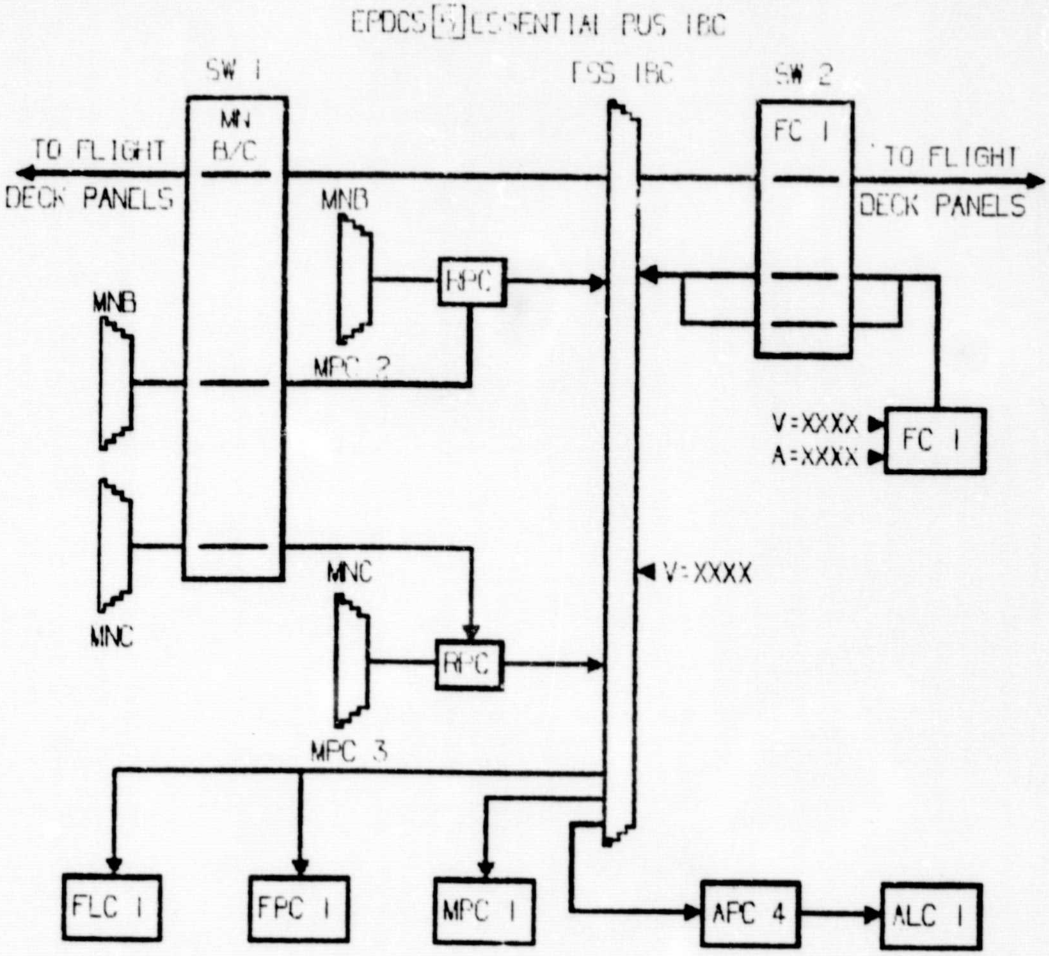

Figure 3.3.2-17 EPDCS ESSENTIAL BUS DISPLAY SHOWING SYSTEM PARAMETERS

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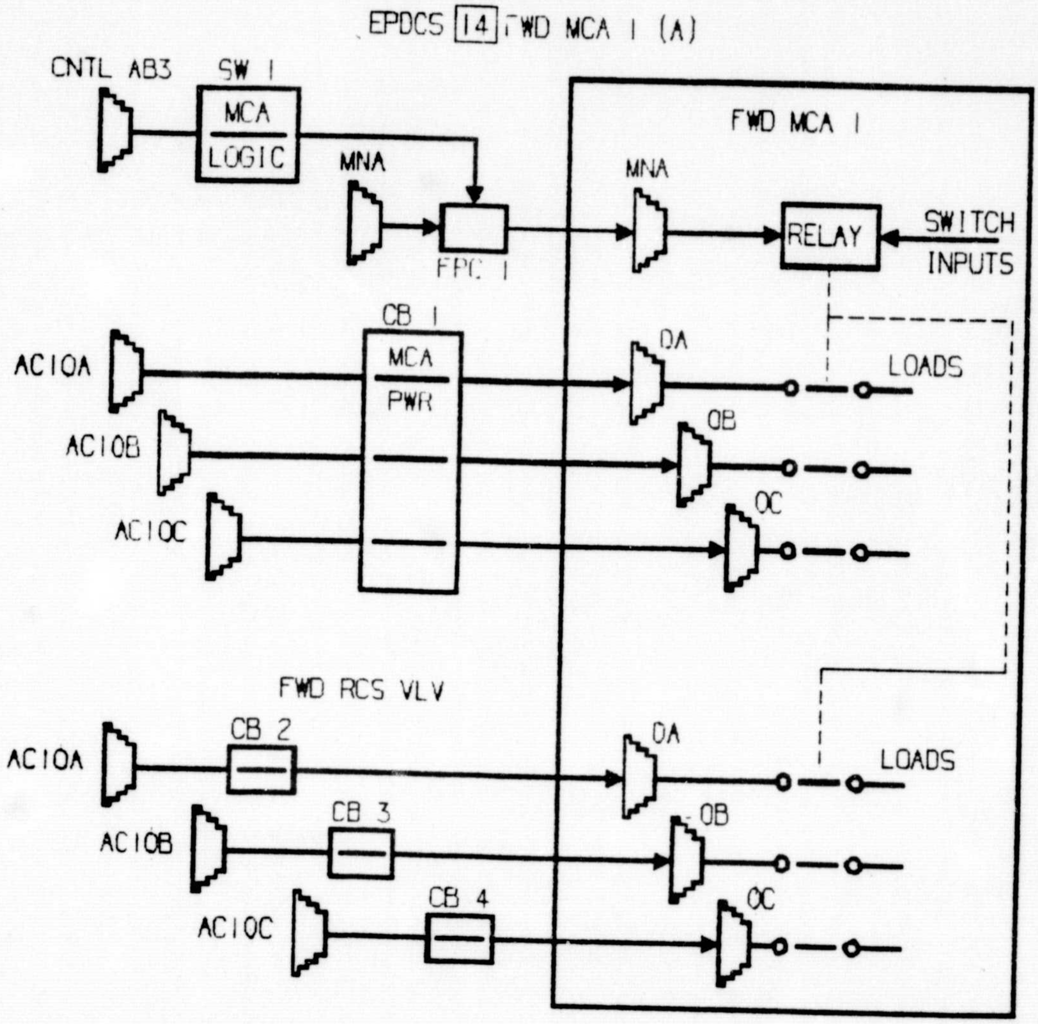


Figure 3.3.2-18 EPDCS FWD MAC 1 (A) DISPLAY

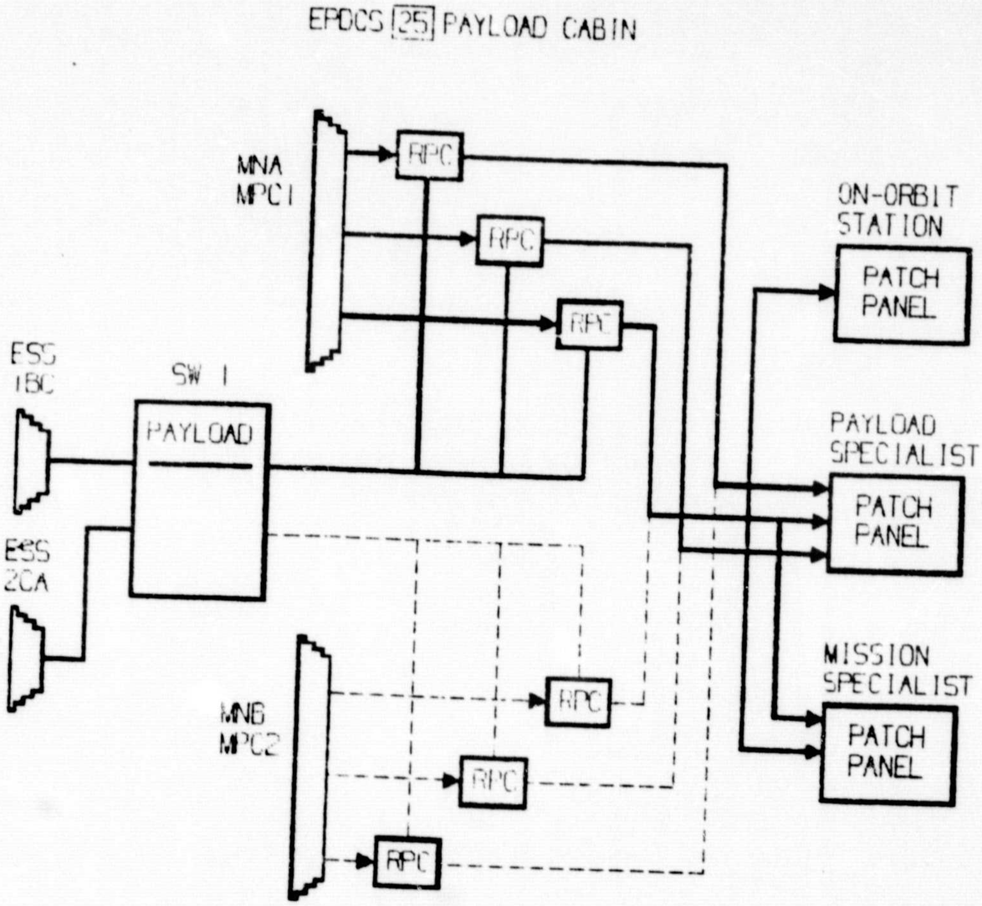


Figure 3.3.2-19 EPDCS PAYLOAD CABIN DISPLAY

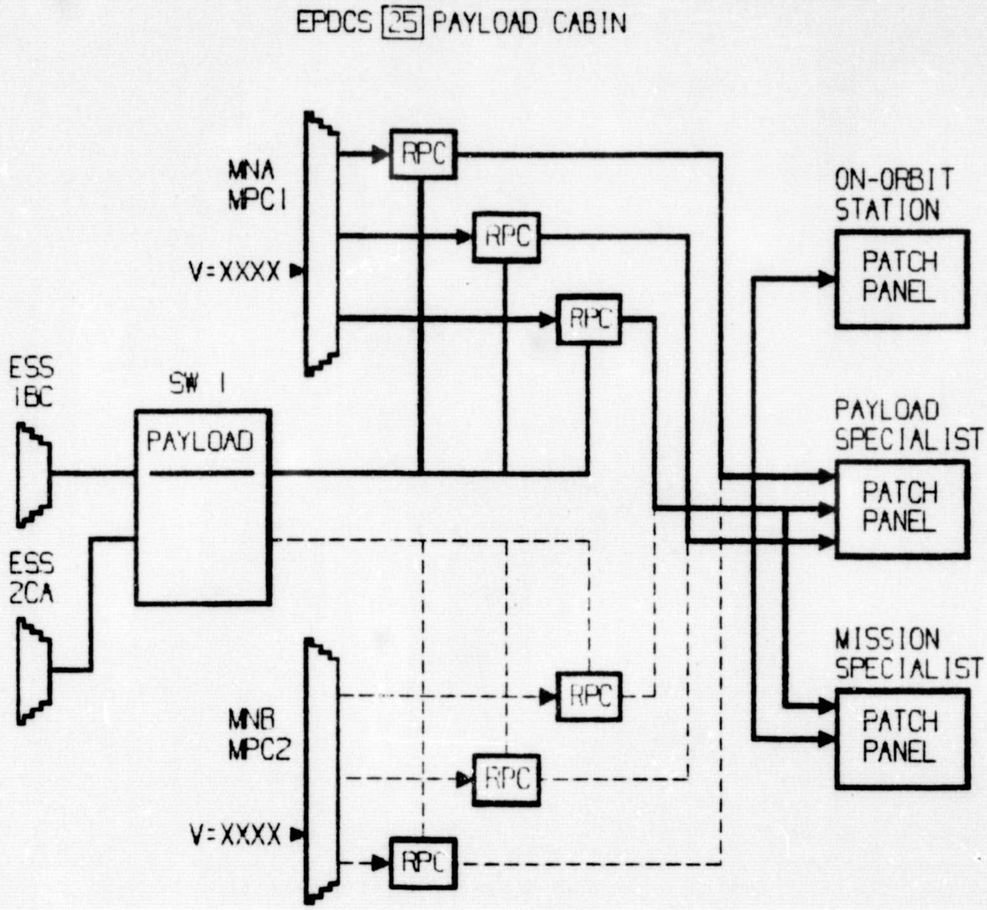


Figure 3.3.2-20 EPDCS PAYLOAD CABIN DISPLAY SHOWING SYSTEM PARAMETERS

TOP LEVEL SUB-SYSTEM SELECTION KEYBOARD
(NON-INTERACTIVE)

OMS	EPDCS	SYST 3	SYST 4
SYST 5	SYST 6	SYST 7	SYST 8
SYST 9	SYST 10	SYST 11	SYST 12

(NOT TO SCALE)

Figure 3.3.2-21 MFDCS SUB-SYSTEM SELECTION KEYBOARD

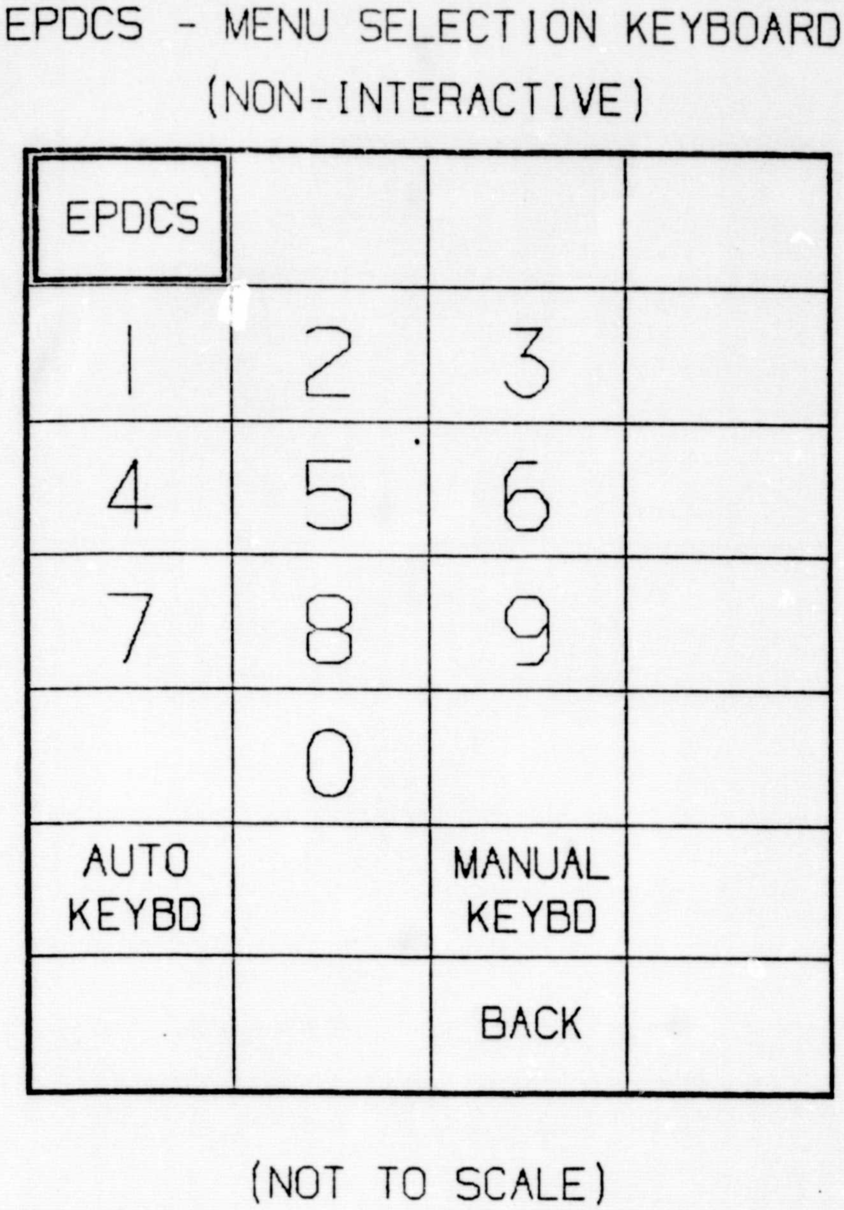


Figure 3.3.2-22 EPDCS - MENU SELECTION KEYBOARD

EPDCS - MANUAL KEYBOARD

(INTERACTIVE)

SW	CB	MNA	MNB
1	2	3	MNC
4	5	6	MON
7	8	9	AUTO TRIP
	0		
ON	OFF	OPEN	RESET
DISPL PARAM	CANCEL	BACK	EXEC

(NOT TO SCALE)

Figure 3.3.2-23 EPDCS - MANUAL KEYBOARD

OMS - MENU SELECTION KEYBOARD
(NON-INTERACTIVE)

OMS			
1	2	3	
4	5	6	
7	8	9	
	0		
AUTO KEYBD		MANUAL KEYBD	
		BACK	

(NOT TO SCALE)

Figure 3.3.2-24 OMS - MENU SELECTION KEYBOARD

OMS - MANUAL KEYBOARD
(INTERACTIVE)

FU	OX	VPR ISOL	ENG SWTCH
1	2	3	ARM
4	5	6	ARM PRESS
7	8	9	KIT
GPC	0		THERM
LEFT	RIGHT	ON OPEN	OFF CLOSE
DISPL PARAM	CANCEL	BACK	EXEC

(NOT TO SCALE)

Figure 3.3.2-25 OMS - MANUAL KEYBOARD

OMS/EPDCS KEYBOARD-AUTOMATIC MODE

(INTERACTIVE WITH CHECKLIST AND/OR SCHEMATIC DISPLAY)

OMS			
CHECK ✓	SKIP ✕	↑	
		↓	DISPL OFF/ON
			TAB OFF/ON
AUTO MODE	MANUAL MODE		
	CANCEL	BACK	EXEC

(NOT TO SCALE)

Figure 3.3.2-26 OMS/EPDCS - AUTOMATIC KEYBOARD

12. N_2 REG. PRESS HIGH
13. N_2 REG. PRESS LOW
14. Ne TANK PRESS LOW
15. PC LOW (DURING BURN)
16. TEMPERATURE LOW (DURING BURN)
17. OMS SECURE

On/off status of the thermal system will always be displayed in all modes.

The OMS ENGINE and PROPELLANT schematics will be color coded as follows: (Figures 3.3.2-1 through 3.3.2-13)

Valve Open - SOLID GREEN
Valve Closed - WHITE
Potential Flow Paths - SOLID GREEN
(He, N_2, FU, OX)

Blocked Flow Path - BROKEN WHITE

System parameters - MAGENTA
(Normal)
System Parameters - YELLOW or ORANGE
(Out-Of-Limit)

Engine Enabled - GREEN
(Eng VLV Switch "ON", Eng Switch - "Arm" or "Arm/Press")

Engine OFF - YELLOW or ORANGE
Either Eng or Eng VLV Switch - "OFF"

Engine Burn - RED

Methods of displaying Thrust Vector Control information pictorially are still being investigated.

Electrical Power Distribution and Control System (EPDCS)

The EPDCS is divided into System Status Displays and Anomaly Response Displays. Access to either menu is obtained by one keystroke. (See Figure 3.3.22).

The tentative System Status menu is listed below. (See Examples Figure 3.3.2-14 through 3.3.2-20)

1. POWER DISTRIBUTION SYSTEM BLOCK DIAGRAM
2. FUEL CELL/MAIN/TIE BUS. #1A
3. FUEL CELL/MAIN/TIE BUS. #2B
4. FUEL CELL/MAIN/TIE BUS. #3C
5. ESS BUS. BC (#1)
6. ESS BUS. CA (#2)
7. ESS BUS. AB (#3)
8. CONTROL BUSES CA, 1, 2, 3
9. CONTROL BUSES BC, 1, 2, 3
10. CONTROL BUSES AB, 1, 2, 3
11. ALTERNATING CURRENT CIRCUIT #1
12. ALTERNATING CURRENT CIRCUIT #2
13. ALTERNATING CURRENT CIRCUIT #3
14. FWD MOTOR CONTROL ASSEM. A (#1)
15. FWD MOTOR CONTROL ASSEM. B (#2)
16. FWD MOTOR CONTROL ASSEM. C (#3)
17. MID MOTOR CONTROL ASSEM. #1 (AB)
18. MID MOTOR CONTROL ASSEM. #2 (BC)
19. MID MOTOR CONTROL ASSEM. #3 (AB)
20. MID MOTOR CONTROL ASSEM. #4 (BC)
21. AFT MOTOR CONTROL ASSEM. A (#1)
22. AFT MOTOR CONTROL ASSEM. B (#2)
23. AFT MOTOR CONTROL ASSEM. C (#3)
24. PAYLOAD POWER INTERFACE
25. PAYLOAD CABIN

The tentative Anomaly Response menu is listed below.

26. FC SHUTDOWN
27. MN A BUS. LOST (INCLUDES AC1)
28. MN B. BUS. LOST (INCLUDES AC2)
29. MN C. BUS. LOST (INCLUDES AC3)
30. AC1 LOST
31. AC2 LOST
32. AC3 LOST
33. 1 FC LOST
34. 2ND. FC LOST
35. ESS 1 BC LOST
36. ESS 2 CA LOST
37. ESS 3 AB LOST
38. CONTROL AB1 LOST
39. CONTROL AB2 LOST
40. CONTROL AB3 LOST
41. CONTROL BC1 LOST
42. CONTROL BC2 LOST
43. CONTROL BC3 LOST
44. CONTROL CA1 LOST
45. CONTROL BC2 LOST
46. CONTROL BC3 LOST

The EPDCS schematics will be color coded as follows:

Energized circuits - SOLID GREEN

Unenergized circuits - BROKEN WHITE

System parameters - MAGENTA (ON COMMAND)
(normal)

System parameters - YELLOW or ORANGE (DISPLAYED AUTOMATICALLY)
(out-of-limits)

Element failure - YELLOW or ORANGE

Operation

Access to the interactive display and keyboard associated with any subsystem segment and/or anomaly response checklist shown in the menu is accomplished by keying the menu number.

All system status segments are displayed schematically. The status of any EPDCS switch or circuit breaker, for example, can be changed by keyboard commands as shown in Figure 3.3.2-23 and 3.3.2-26.

Anomaly response checklist procedures are displayed on the flat panel display. Procedures which address other subsystems in addition to the EPDCS usually will not require a schematic.

In the AUTO mode the computer sequentically performs each task of the displayed checklist, placing a check mark by each completed task when checked off by the operator. Should the operator choose to skip any task he may do so by pressing the SKIP key and the remaining tasks will continue to be performed.

3.3.3 System Operation

As discussed in Section 2, the MFDCS is designed to operate in four modes. These modes are illustrated in Figure 3.3.3-1. The top level of the system is the system status mode in which the operator has access to all MFDCS subsystems. The high resolution graphics display presents a block diagram of systems under MFDCS control. The keyboard display for this level is illustrated in Figure 3.3.2-21. If no caution and warnings are present, the system may be operated in the normal mode. In this mode a system (such as OMS) is selected from the top level keyboard. This selection brings up a menu of normal operations for that system on the high resolution display and provides the operator with a keyboard display to select the procedure desired (see Figure 3.3.2-24). The operator enters the procedure selection number from the menu and indicates whether an automatic option or single function (manual) access is desired. At this point the procedure appears on the checklist display and in the automatic option the keyboard shown in Figure 3.3.2-26 would appear. Activation of the Auto Mode Key followed by the EXEC key will cycle through the whole procedure automatically. A single step mode is available at any time through the MANUAL MODE key. CANCEL eliminates an action before execution. A basic ground rule

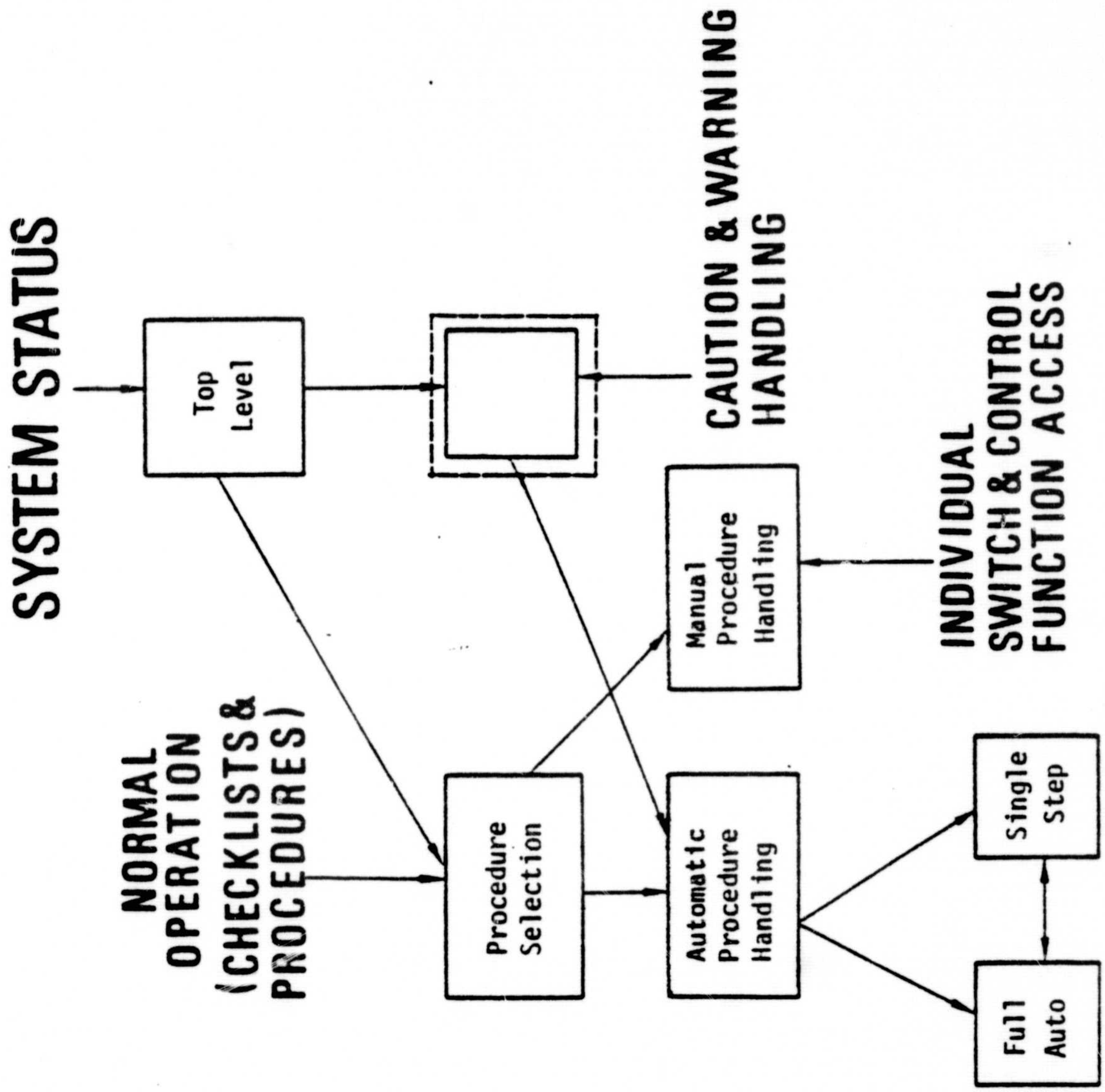


Figure 3.3.3-1 MFDCS OPERATING STRUCTURE

in the system is the requirement for activation of the EXEC key in manual modes for all command functions which change the system configuration. BACK returns the operator to the previous page. If the MANUAL KEYBD option is selected then the operator must address each valve or control using the manual keyboard (Figure 3.3.2-25) the checklist display procedure, and the status indication on the schematic display. At this point, he is in the Individual Switch and Control Function Access Mode.

If a caution and warning (C&W) signal occurs, the problem will be displayed at the bottom of the CRT and/or scratchpad display together with a suggested procedure. Multiple C&W's will be prioritized with respect to system impact. In the normal mode the operator simply backs up to the top level using the BACK key and from there accesses the C&W mode. In the event that a C&W of overriding importance occurs, the keyboard can exhibit a forced display requiring operator acceptance or rejection of C&W action. Rejection will remove the forced display. Acceptance will take the operator directly to the C&W mode, eliminating the need to back up to the top and then access from there. Once in the C&W mode, the operator will be presented with a heirarchial list of procedures accompanying the prioritized C&W messages. Selection of a procedure leads to the automatic procedure handling area of the normal operation mode.

3.3.4 Display Parameters

Multifunction displays present primarily alphanumeric symbols, special symbols and perhaps a few graphics primaries (lines, arcs, etc.). The numerous human factors parameters relevant to the display of these types of information have been summarized in several sources (References 3-1, 3-2, 3-3). Only a few of the major issues and parameters are covered here.

3.3.4.1 Symbol Legibility Parameters

Overall system performance will be influenced by the speed and accuracy with which the human operator can transfer the CRT displayed information into cognative action. Many variables such as symbol size, stroke width, format, style, leading, symbol luminous intensity and ambient illuminance modulate legibility.

Important variables that are under the direct control of the system designer are symbol displayed size, ratio of height to width of the symbol, stroke width to height, and luminous intensity of the elements within the symbols.

Luminous contrast and image blur are factors that may be altered by the working environment. As a spacecraft moves the ambient illumination may change and this will alter the luminous contrast of alphanumerics that have a fixed luminious intensity. Vehicle vibration or a defocused electron beam in the CRT may impose physical or apparent blur of the visual image. Whereas the designer may choose to use larger visual stimuli to gain acceptable legibility and less degradation by higher contrast and lower blur, he must consider the practical aspects of decreasing the amount of information he may be able to display. As pointed out by Semple (Reference 3-3), "Limitations on available display space, considerations of information density, and general economic constraints often compel the systems designer to employ symbols no larger than those required to met the legibility requirements of the system task". It is important to establish the acceptable symbol subtense required for legibility when contrast and blur may be varied by operational factors especially when the particular display applications are known.

Numerous recommendations have been made for minimum symbol size. The required size differs with the manner of presentation, the characteristics of the symbol font and the particular application. Referring to the latter category, for example, larger characters should be provided when correct discrimination of each character is critical, when speed and ease of reading are important, and when each symbol is independent, as in a code number, rather than being partially redundant as in typical English text. Typical minimum symbol height recommendations are 15 to 25 arc minutes (Reference 3-2, 3-4). A frequently suggested character height is 5mm (0.2 inches) for flight deck applications where a common viewing distance is 70cm (28 inches). This corresponds to an angular size of 24 arc minutes. Extremely critical data that must be read with extreme speed should be displayed using larger characters.

Several investigators have studied the effects of symbol subtense on operator performance. Of these, the studies that employed quantitative methods and multiple variables have had similar results. In a classic and still relevant study Howell and Kraft (Reference 3-5) investigated the relation of functions of relating size, blur, and contrast to legibility. Howell and Kraft used a slight modification of the Mackworth alphanumerics (Reference 3-6) on a radar-type display. The symbol sizes in terms of angles subtended by the height of the stimulus (letters and numbers) were 36.8, 26.8, 16.4 and 6.0 minutes of arc. The solid-line white-on-black printed symbols were projected one at a time on the ground-glass screen at a rate controlled by the subjects' responses. Legibility was measured in terms of rate and accuracy of symbol identification. There were three variables: (a) size of the symbols as

just discussed, (b) contrast or brightness of the symbols relative to a constant background brightness, and (c) blurredness of the image which was defined as the rate oi transitions between the brightness of the symbols and that of the field.

The interactions among these dimensions are especially worthy of reporting. For example, it is important to know the extent to which increased size can compensate for increased blur and reduced contrast. Also, it is desirable to know the optimum combination of the three dimensions as well as the loss in legibility incurred by deviations from this optimum.

It is apparent from the information scores, as well as from the time and error data, that some minimal size (probably around 16 minutes of visual angle of letter height) must be exceeded before any practical degree of legibility can be attained. Futhermore, the reduction in legibility below this minimal point is extremely rapid as indicated by the steepness of the curve between the two smallest sizes in Figures 3.3.4.1-1, -2 and -3. As size is increased above 16 arc minutes, however, there is relatively little improvement in legibility except under conditions of reduced contrast and/or increased blur. These findings are in general accordance with those reported by Crook et al., in Reference 3-7 both with respect to the size function and the high degree of interaction obtained among dimensions.

The major implications of these findings for operational use are these: (a) in a situation employing white-on-black alpha-numeric symbols, maximum legibility may be attained when no blur exists, contrast is at or above 37, and size is approximately 27 minutes of visual angle (letter height), and (b) if the situation imposes restrictions on any of these values, the loss may be minimized by adjusting the values along the other dimensions in accordance with Figures 3.3.4.1-1, -2 and -3.

It is important to note that a reduction to 16.4 minutes of letter height produced a negligible drop in legibility so long as the other variables were at their optimum. When either or both of these were diminished, or when size was reduced still further, performance dropped off rapidly.

In an evaluation of two letter sizes, 0.40cm and 0.48cm, for this application, 0.40cm inch high letters were found to be "acceptable" and the 0.48cm 3/16 letters were "ideal" for eye-to-display distances between 61 and 71cm. The following table illustrates that these observations conform with the experimental data.

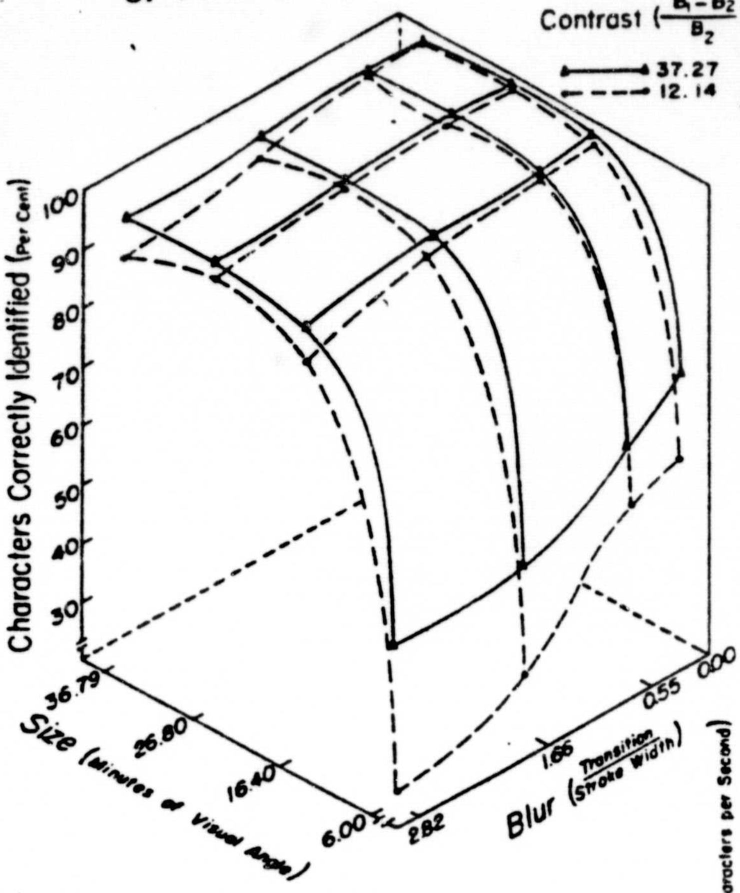
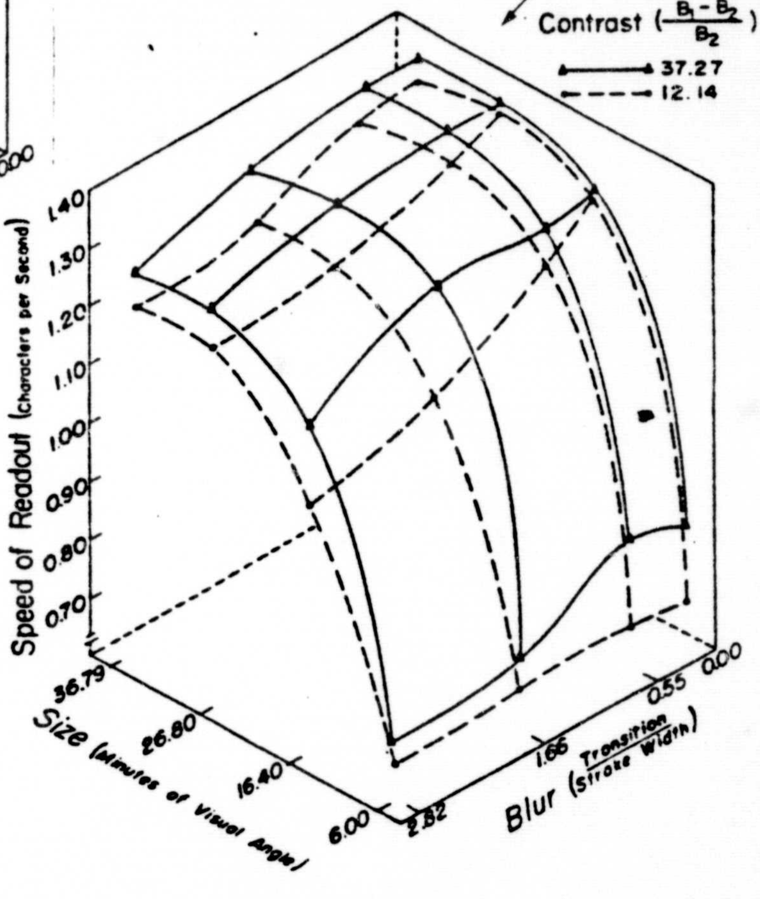


Figure 3.3.4.1-1 CHARACTER IDENTIFICATION

Percent of characters correctly identified as a function of size, blur, and contrast of letter and numbers.

Figure 3.3.4.1-2 READOUT SPEED

Speed of readout of letters and numbers as a function of size, blur, and contrast of letters and numbers.



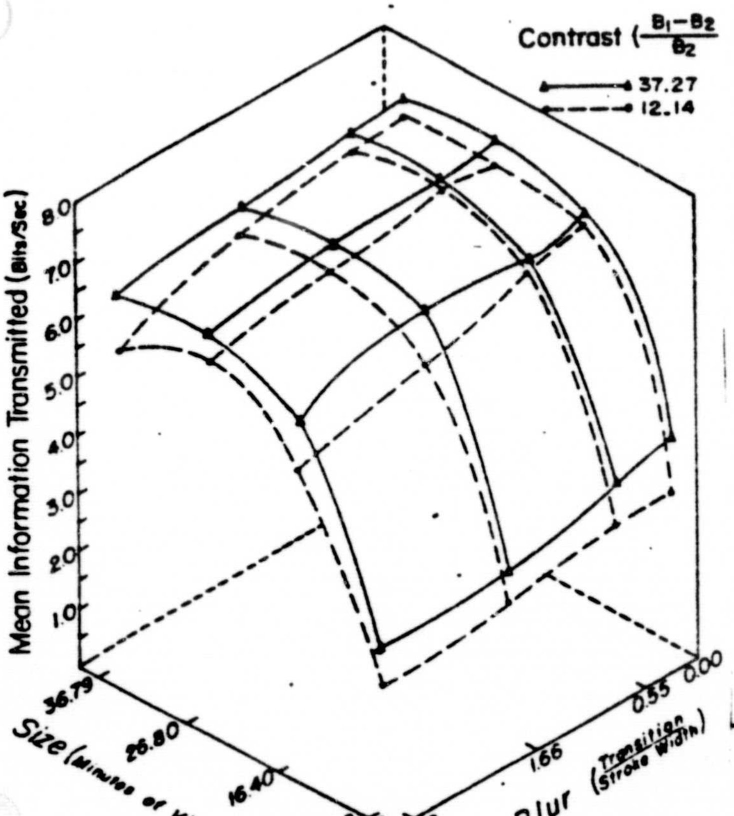


Figure 3.3.4.1-3 INFORMATION TRANSMISSION

Mean information transmitted (bits/second) as a function of size, blur, and contrast of letters.

TABLE 3.3.4.1-1

VISUAL ANGLE SUBTENDED BY TWO LETTER HEIGHTS AT THREE VIEWING DISTANCES

Letter Height		Viewing Distances In Centimeters (Inches)		
		61 (24.)	66 (26.)	71 (28.)
0.40cm	(5/32 inch)	22.38	20.66	19.18 arc min.
0.48cm	(3/16 inch)	26.85	24.79	23.02 arc min.

The ideal is the 0.48cm height symbol at a 61cm viewing distance and with this height, 37% contrast and minimum blur the accuracy is expected to be 97% correct interpretations. With single characters presented one at a time the speed would exceed 1.35 characters per second.

These values are for stroke widths of 1/8th the height of the letter and for letter widths 60% of the letter height, or values ideal for translighted or self luminous symbols seen against a black background.

The issue of minimum contrast is also complicated by the existence of numerous recommendations and interaction with many other parameters. If the symbol contrast is too low, discrimination is difficult and time consuming. As the contrast increases, the symbol becomes more easily visible until a point is reached where the contrast is so high that the image "blooms" and becomes less visible. A minimum contrast ratio of 5 has been suggested for "at-a-glance" viewing under daylight conditions (Reference 3-4). The same source suggests an upper limit on the contrast ratio of about 80.

Measurement of the visual contrast of modern displays is complicated by the fact that some of these devices particularly LED displays, emit light from several very small discrete areas. If these areas are smaller than about 0.7 to 1 arc minute, luminance measurements for determinimg effective display contrast should be made over an area about this large (Reference 3-4).

Color introduces another factor into the problem of contrast determination. If the color of a symbol and the background are markedly different this "color contrast" can add to the luminance contrast discussed in the previous two paragraphs to yield a higher effective contrast. Methods of computing the contribution of color to contrast have been proposed (References 3-8, 3-9).

The color of a display also affects the extent to which ambient light falling on the display reduces contrast. Typical white ambient illumination, either day light or artificially generated light, contains more effective energy in the green than in the red region. As a result, green and amber displays are more susceptible to contrast loss from ambient illumination. Band pass filters are often used with these displays to reduce the contrast loss resulting from ambient light reflections from areas that are not activated. Although higher contrast can usually be obtained with red rather than with amber or green displays in a high ambient illumination environment, red should usually be reserved for displaying information related to warnings and hazardous conditions.

3.3.4.2 Dot Matrix Display Parameters

Dot matrix displays use discrete elements that can be selectively activated to form symbols. Common examples include LED, LCD, TFEL, plasma and vacuum fluorescent displays. Raster-type CRT displays also fall into this category, but the individual dots or elements are blurred rather than sharp edged.

The number of elements in the matrix must be sufficient to allow discrimination between all displayed symbols. If only numerals and uppercase English letters are to be displayed and if other requirements such as size and contrast are met, a matrix five elements wide by seven elements high is adequate for generating each symbol (Reference 3-10). Additional elements or an open space is required to separate characters. If lower case characters are to be displayed, the number of elements should be increased to 7 by 11 (Reference 3-11) or 8 by 11 (Reference 3-4). Even more elements are useful if the characters are to be rotated, and to prevent degradation in legibility due to failed display elements.

The elements making up the matrix usually do not entirely fill the matrix, but are separated by a finite distance. The proportion of the matrix area that is active (that is, changes color when activated) can affect character legibility. In general, the greater the proportion of area that is active, the easier the symbol is to resolve. This relationship has been demonstrated for active area proportions up to about 0.5 using a 5 by 7 matrix (Reference 3-1, 3-12, 3-13, 3-14), which corresponds to a spacing between square display elements slightly less than half the width of the active region. The importance of the proportion of active area is greatest if the task is difficult, either because of some visibility factor such as low contrast or because of time pressure to read the characters rapidly.

The character font used with a particular display has a major affect on legibility. With a good font, there will be fewer errors because each character is easily recognized and easily distinquished from all other characters in the set. These two requirements are partially contradictory. That is, the difference between characters can be increased but this can result in some of the characters being unfamiliar and hence more difficult to recognize or less acceptable esthetically. The recommended font in Figure 3.3.4.2-1 represents a compromise in this area. For example, the "B" and the "8" are both distorted slightly to make them more distinquishable, and a slash has been added to the numeral "0" to distinquish it from the letter "O". However, a horizontal bar was not added in the center of the "Z" because this was too large a deviation from current tradition even though it would have made the "Z" more distinquishable from the "2".

The design of a font is becomes most important when the minimum number of display elements are available to generate the character. The recommended font in Figure 3.3.4.2-1 utilizes the minimum effective matrix size of 5 by 7 elements. It is primarily the Huddleston font (Reference 3-15), which in a 5 by 7 by size has been found to provide character legibility superior to other fonts (Reference 3-14). The font shown in Figure 3.3.4.2-1 has been changed slightly from the sample in Reference 3-16. The width of the internal segments of characters "M", "N", "W" and "X" has been reduced, making these more compatible with the other characters in the font and reducing slightly the number of elements that are simultaneously illuminated. Also, the horizontal in the center of the "P" has been moved down one space so that it is separated from the upper bar by two spaces rather than only one. This makes it slightly more similar in appearance to the "F", but elimates the chance that failure of a single element could convert a "P" to an "F". Also, the "2" has been modified slightly to make it more distinctive from the "Z".

3.4 Correlation of Design Performance and System Requirements

The basis for the operator interaction with the MFDCS is through the displays and controls presented. As a result, a primary emphasis in the analysis of the MFDCS hardware alternatives was placed on the display and control alternatives. Requirements for the remainder of the system are determined, to a large extent, by the display and control choices.

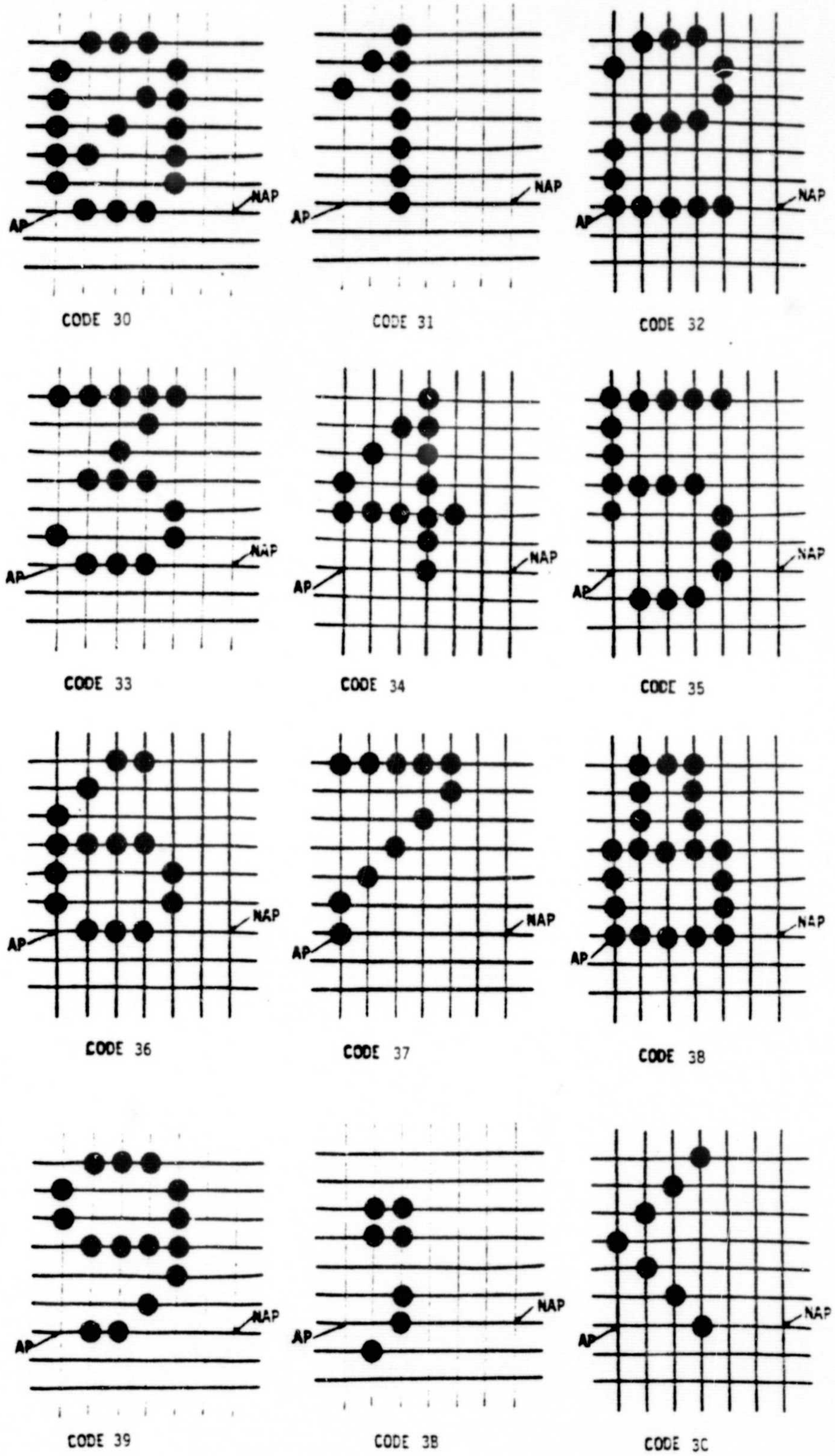


Figure 3.3.4.2-1 CHARACTER AND SYMBOL FORMATS

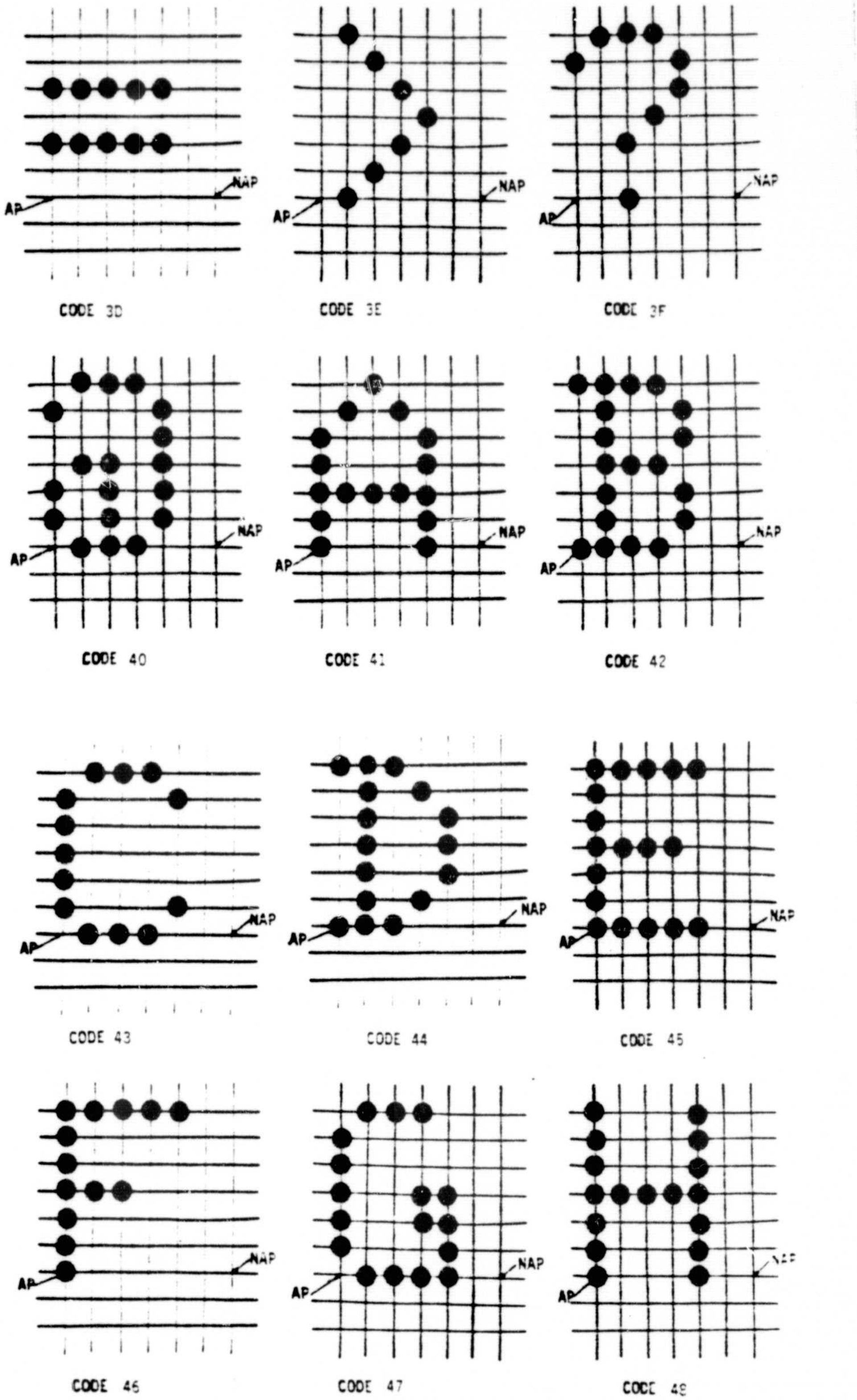


Figure 3.3.4.2-1 CHARACTER AND SYMBOL FORMATS (CONTINUED)

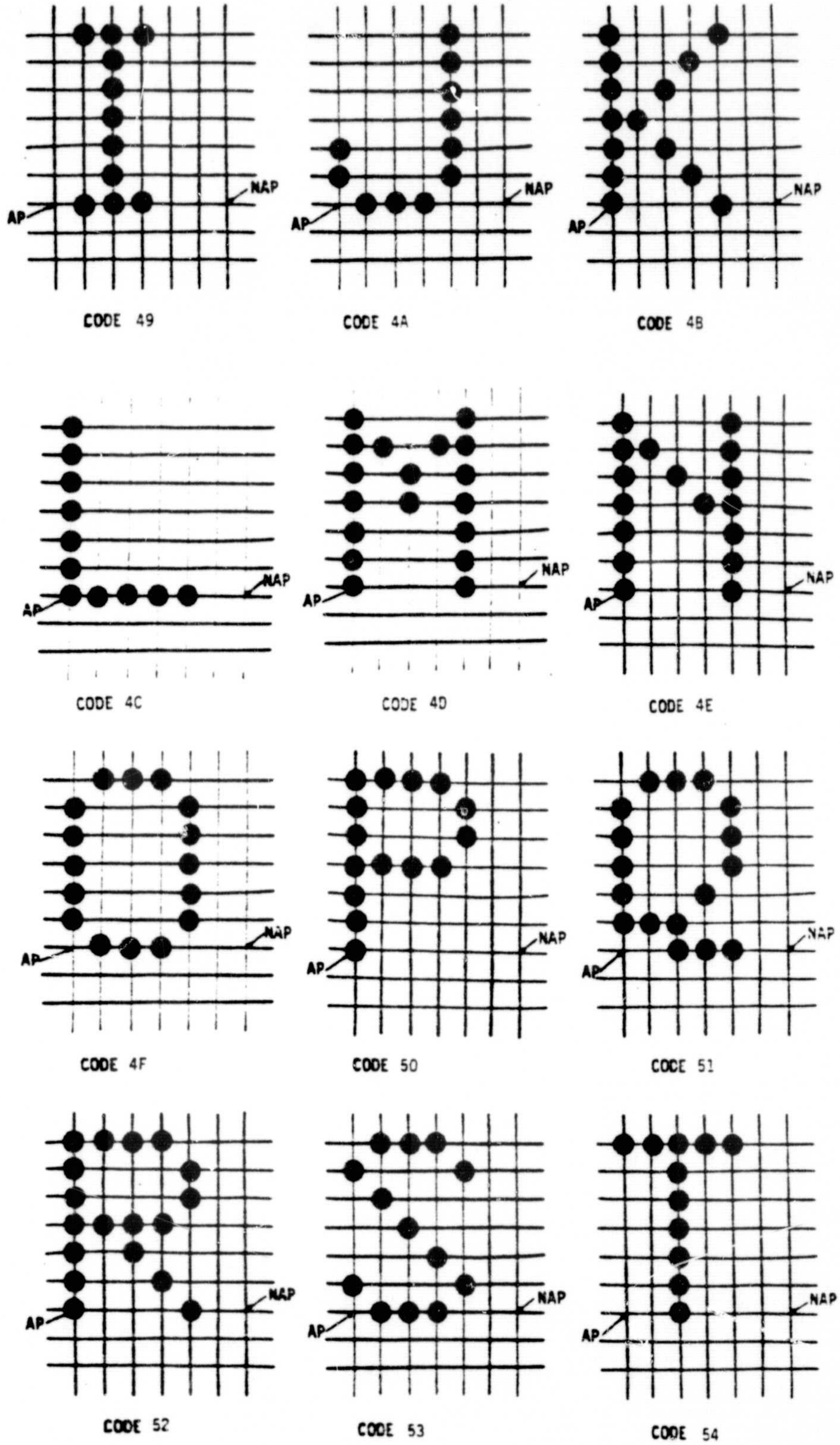


Figure 3.3.4.2-1 CHARACTER AND SYMBOL FORMATS (CONTINUED)

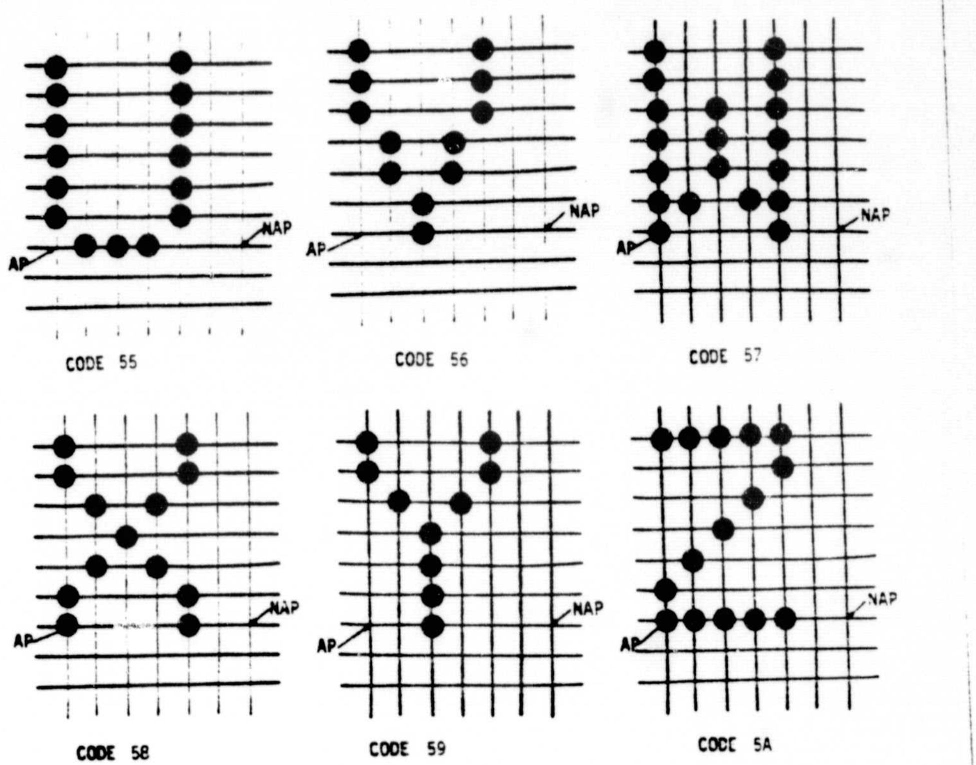


Figure 3.3.4.2-1 CHARACTER AND SYMBOL FORMATS (CONTINUED)

3.4.1 Display Analysis

The first step in the analysis of display hardware was a compilation of the displays necessary for presentation of the OMS and EPDCS status and configuration. The most complex display image developed was that showing the OMS configuration (see Figure 3.4-1). This image was produced on a monochrome CRT tube in a 768 x 768 pixel format. Color was added to photographically reproduced copies of the image and was judged by observers to enhance considerably the comprehension of the display. As a result, color was assumed to be a desirable feature for the high resolution display. Color choice was discussed in Section 3.3 and requires a full color (RGB) display. Current technology limits display choices to the CRT for a full color requirement. Within CRT technology the new color displays developed for cockpit use by firms such as Sperry and Collins represent examples of displays with the necessary resolution and brightness for use in a cockpit environment. For the OMS display, a CRT image area approximately 18 x 18cm (7 x 7 inches) is needed to provide sufficient character height for alphanumeric data. Consideration of the use of a single large display for presentation of high resolution graphics, checklists and procedures, and a keyboard area presents a number of problems: 1) Although the number of displays would be minimized, the full color capability is not necessary for the checklists and keyboard. The 18 x 18cm size requirement would be increased to an approximate size of 18 x 28cm which is larger than currently available high brightness color displays. For example, the 18 x 18cm size approximates the large (size D) model currently offered by Sperry. 2) The high brightness displays have high power requirements. Earlier discussions with NASA-JSC indicated that the high resolution display would not be needed during much of the mission. Considerable power can be saved by separating the keyboard and checklist displays, thus allowing the high resolution display to be turned off part of the time. Power consumption on a size D Sperry display is listed at approximately 215 watts, giving a power per unit area of ~ 0.75 watts/cm^2. Figure 3.4-2 compares this figure with comparable examples of other displays. The passive LCD display is very low in power requirements, but would require auxiliary lighting at low light levels. The use of TFEL displays for the checklist and keyboard displays for example would save ~ 100 watts of power if all displays were on. For a LED array this figure would be approximately 60 watts. 3) The large area screen would require a touch panel overlay for at least the keyboard portion of the display. The principal drawbacks to the touch panel in the Orbiter environment are the necessity to guard against accidental activation and against damage to the thin film forming the panel. An additional disadvantage is the lack of a positive tactile feedback to the operator when activating the panel. The use of bezel switches with a large single display would be limited by the minimized perimeter area around each of the separate display regions on the screen.

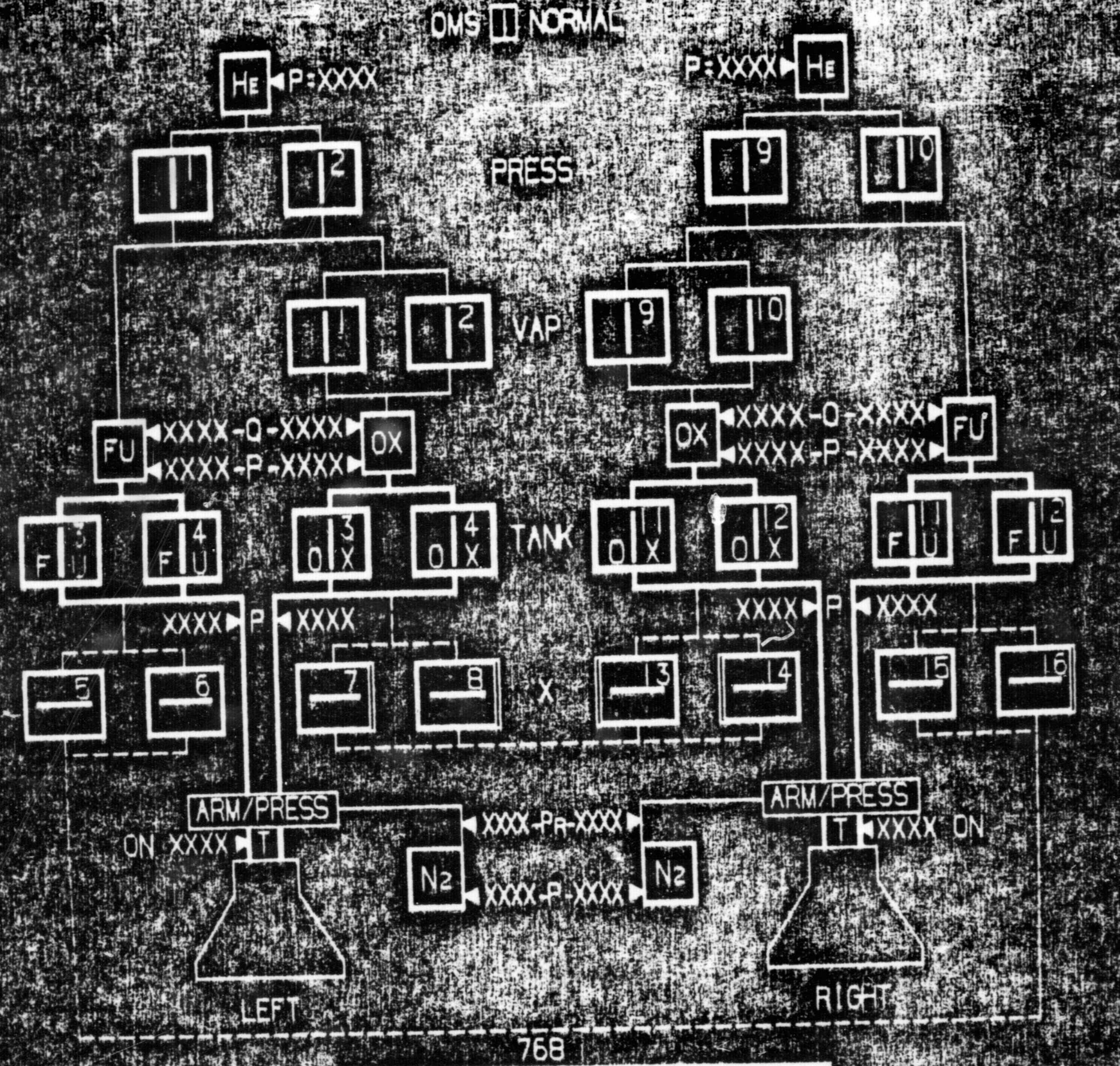


Figure 3.4-1 OMS SCHEMATIC DISPLAY

ORIGINAL PAGE IS OF POOR QUALITY

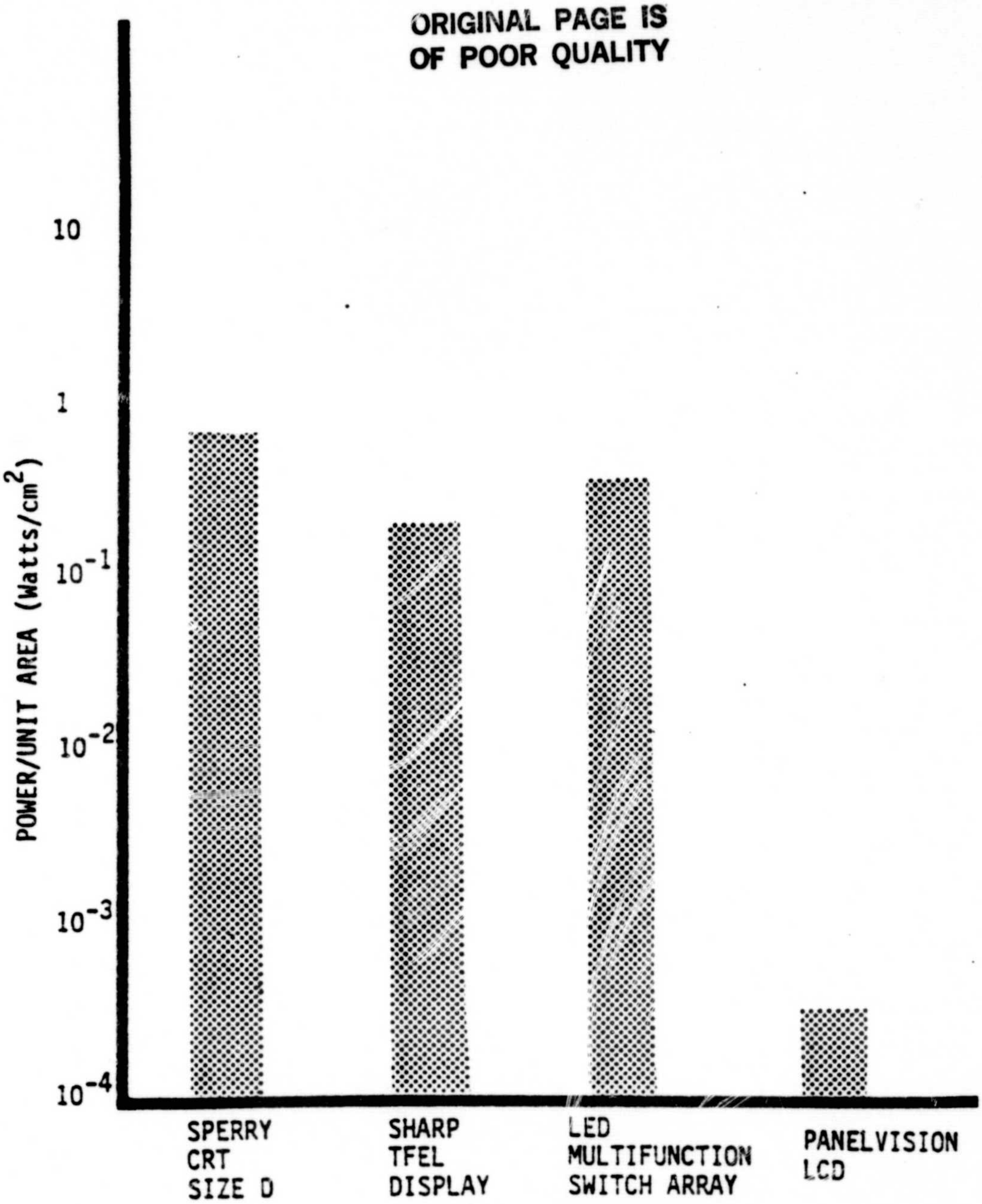


Figure 3.4-2 POWER/UNIT AREA FOR VARIOUS DISPLAY FORMS

If flat panel displays are used for the keyboard and checklist display areas, principal questions again include the use of individual switches vs. touch panels and the choice of flat panel display type to be used in each area. Individual switches can be arranged in either a keyboard array or as bezel edit switches on the perimeter of the flat panels. The use of bezel edit switches or a touch panel on the checklist display area would typically be for a menu selection activity. The requirements on spacing of lines to provide sufficient space for single switch or touch area activation would result in display areas excessively large for the space on Panel R1 due to the length of some of the OMS and EPDCS menus. This problem is compounded by the decrease in the precision of operator touch placement which can be caused by the longitudinal acceleration during launch and/or by the potential necessity of operating in a gloved and suited environment. Given the number of switches (28) required on the keyboard area, the use of bezel edit switches would produce the same panel space problem as mentioned above for the checklist display. The grouping of switches into a multifunction keyboard array can be accomplished using either a touch panel or individual programmable legend switches. In the present Orbiter keyboards, the individual switches are separated by guard fences to prevent accidental or dual activation. The fence structure using a touch panel would require that the switch areas be recessed which implies a limitation on viewing angle. Individual switches could be placed nearly flush with the outer fence structure surface. Another advantage of the individual switches is the availability of a positive tactile feedback to the operator upon activation.

The choice of a display type for the flat panel areas is limited at this time to those available on the market. Development for a future time frame will probably change the choices considerably. At this time, panels for the scratchpad area exist in several technologies. These include LED, AC plasma, vacuum flourescence (VF), thin film electroluminescense (TFEL), and liquid crystal display (LCD). As a passive display, the LCD panel offers the greatest savings in power combined with low voltage operation. One version of LCD panel (Kylex) requires power only when the display changes. Prinicpal drawbacks to the LCD panels are a requirement for auxilliary lighting in low light conditions and slow reaction time at temperatures below $0^{\circ}C$. Typical costs for a 10 x 12cm panel are on the order of $2-5K. At this time the order of consideration indicated for the final design would be LCD, TFEL and LED based on power consumption, availability and cooling requirements.

Flat panel displays in the form of individual switches are just being developed and are currenly available only with LED displays. LCD displays could be used as a switch display with relatively little development and should be looked at as an alternative to the LED

display. TFEL switch displays are viewed as a replacement for LED switches within a 5 year time frame.

Display resolution requirements were judged most stringent for the graphics display. Most of the display resolution effort was directed towards a definition of the most complex display example and a test of resolution options for that display. The test process is described in Section 4. The OMS display was produced in a number of resolutions ranging from 128 to 768 pixels on a side. Resolutions from 256 to 768 are shown in Figure 3.4-3a, b c. The number of pixels used is shown at the bottom of each display. The range from 256 to 512 pixels is not satisfactory for the alphanumeric characters and even at 512 pixels, only marginal for the graphic outlines. The 645 and 768 pixel examples are satisfactory for the graphic outlines but still show a considerable stairstepping effect for the characters. Operating in a high resolution raster mode adds greatly to the memory requirements imposed on the system. The raster display of seven colors requires 3 bits of data to define the color and a memory plane equivalent to the number of pixels. Thus a 256 x 256 display requires ~200K bits of memory while a 1024 x 1024 display would require 3.2M bits. This problem is solved in the current cockpit color CRT displays by the use of a hybrid system in which the lines and characters are stroke written and the solid color areas are filled as a 256 line raster display. Widening the stroke widths to cover more than one shadow mask element is employed to eliminate an appearance of stairstepping. In the stroke mode, only the vector end points need to be specified in the memory. This appraoch not only reduces the memory requirement but also decreases the required processing to refresh the display.

Resolution requirements on the flat panel displays are less stringent. This is due in part to the sharp edge definition of the pixels in most of the flat panel displays compared to the graduation of intensity over the area of a CRT pixel. Comparison of a 192 line TFEL display with a 192 line CRT display format showed a much crisper alphanumeric image on the TFEL display given the same ratio of character size to viewing distance. On the other had, the technique used in the stroke writen mode, describd above, to reduce stairstepping is not as easily applicable to the flat panel displays.

3.4.2 Processing Analysis

A first step in analysis of the processor requirements was the decision on how the system was to be partitioned given the desired display complement. A desirable criterion was that the various display components be modifiable as time progressed without affecting the

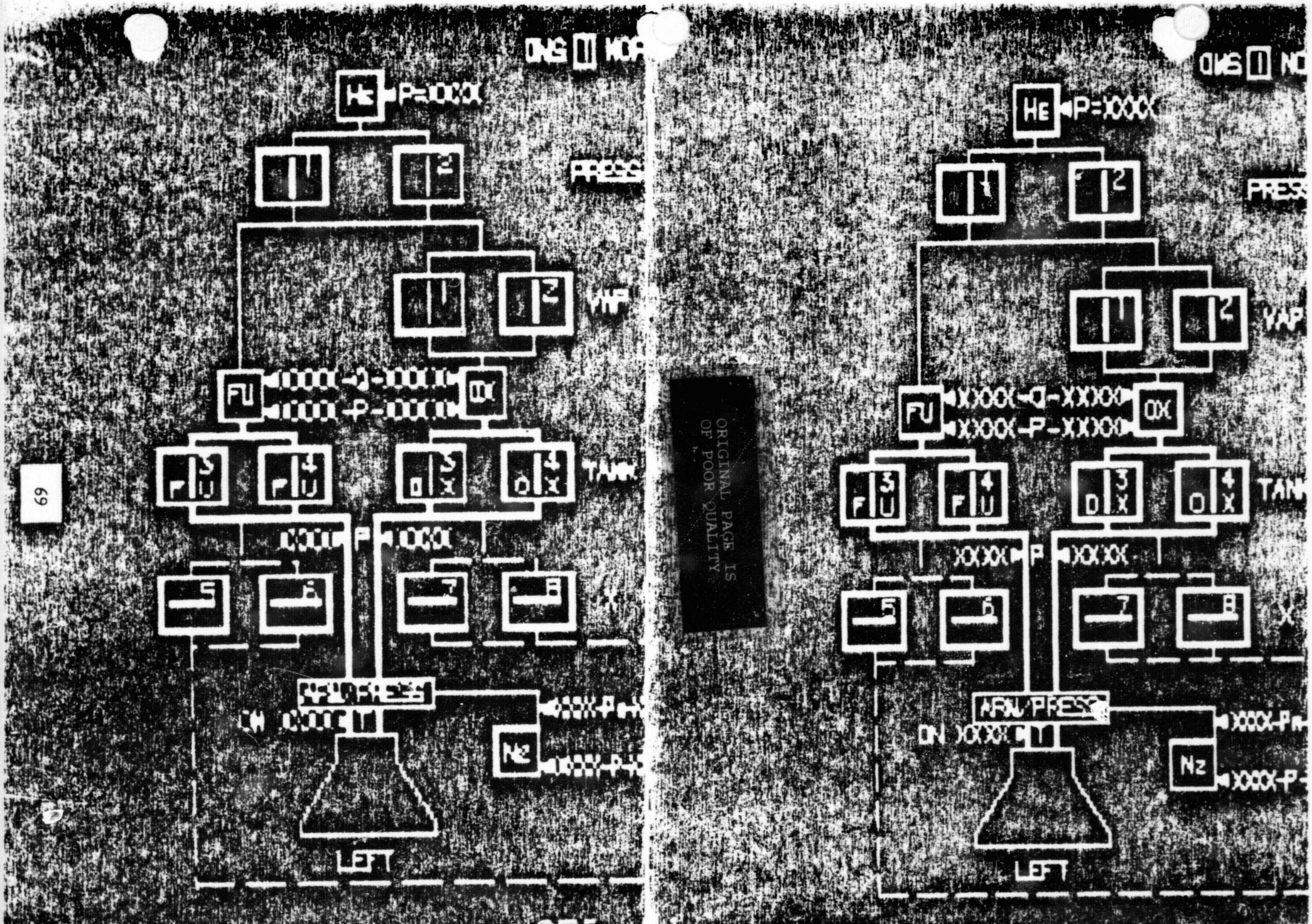


Figure 3.4-3a DISPLAY RESOLUTION TEST

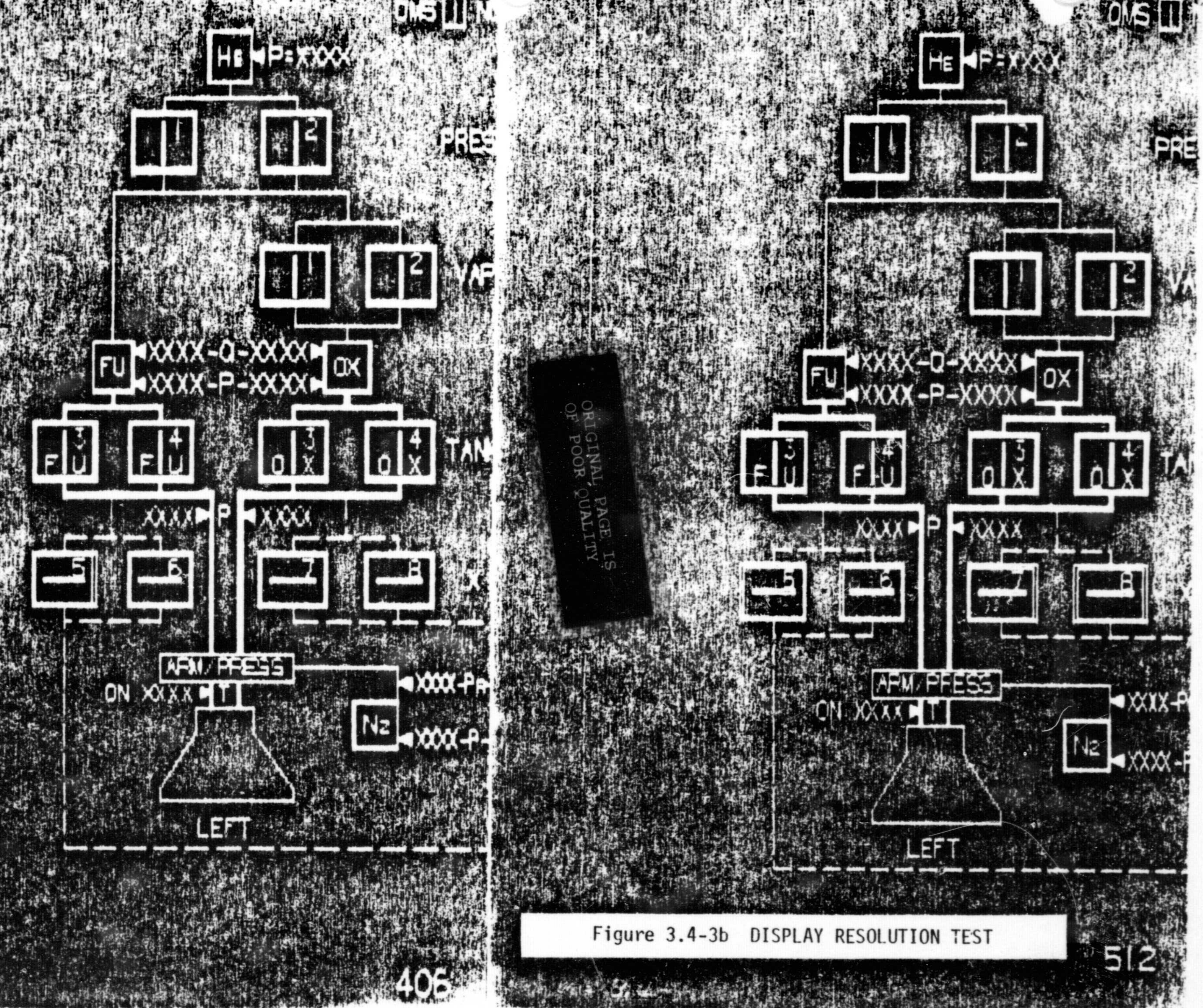


Figure 3.4-3b DISPLAY RESOLUTION TEST

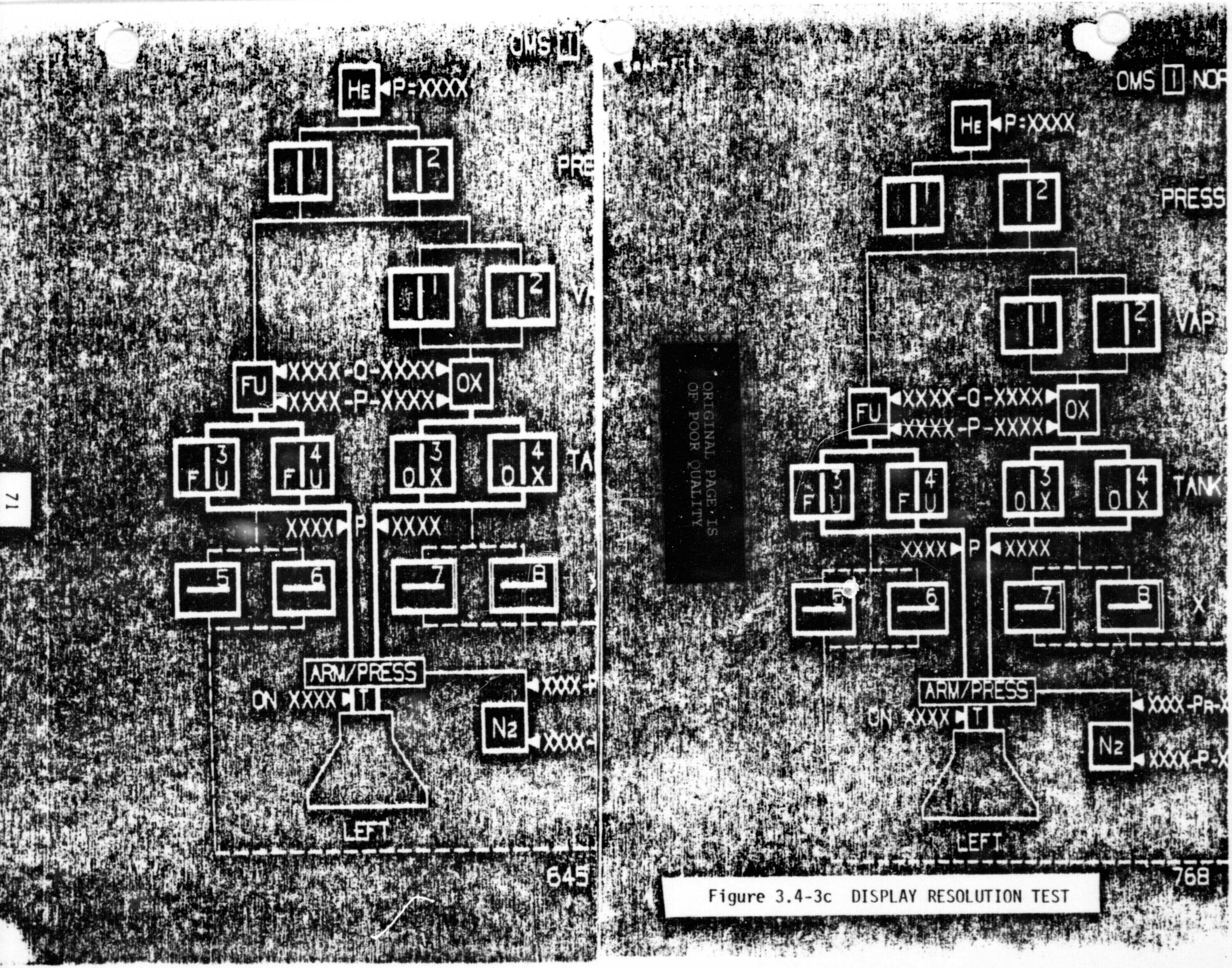


Figure 3.4-3c DISPLAY RESOLUTION TEST

whole system. In addition, an estimate of the processing time required to maintain the refreshing of LED multifunction switches, a medium resolution checklist display and a high resolution graphics display showed that a single processor would be too heavily loaded to provide rapid response times. A goal of ≤ 0.2 seconds was set for the update of the keyboard displays. Similarly the desired update time for the checklist display was set somewhat higher at ≤ 0.8 seconds. Update time for the high resolution displays was permitted greater latitude with a time on the order of 1 second being deemed satisfactory. The updata rate for dynamic subsegments of the high resolution display however, was targeted at ≤ 0.2 as in the case of the keyboard update.

To permit higher speed operation, the MFDCS processing was divided into several subsegments. The central controller processor handles the storage and distribution of commands and legends to the keyboard and checklist display. In addition, the central controller hendles the communications with the host computer (GPC). Available multifunction switches are operated in groups of four with each group interfacing to a controller via a Z8 microprocessor. The Z8 receives data from the controller for display on the switch legends and provides switch action information and status conditions to the controller

The large number of checklist and procedures to be displayed on the medium resolution display require a considerable amount of memory. A flat panel Sharp TFEL display, for example, portraying 20 lines of 32 character alphanumeric information will require approximately 9.6k bytes of memory. For this reason, the medium resolution display was assigned its own processor and memory.

The display actually chosen for the high resolution graphics will define the processor configuration used. The graphics display will in general, require its own memory and processor for the storage of images and dyn;amic modification of the display. Commands from the controller will define the image and/or the subsegment modification to be made. The majority of the image will remain static. For example, in Figure 3.4-1 the opening of a valve in the OMS will be indicated by changing the orientation of the bar in the valve symbol. The arrangement of the processing architecture described above is indicated in Figure 3.4-4.

An analysis of the processing speed and memory required for the controller processor was conducted using two different processors to represent 8 bit (Intel 8085) and 16 bit (Intel

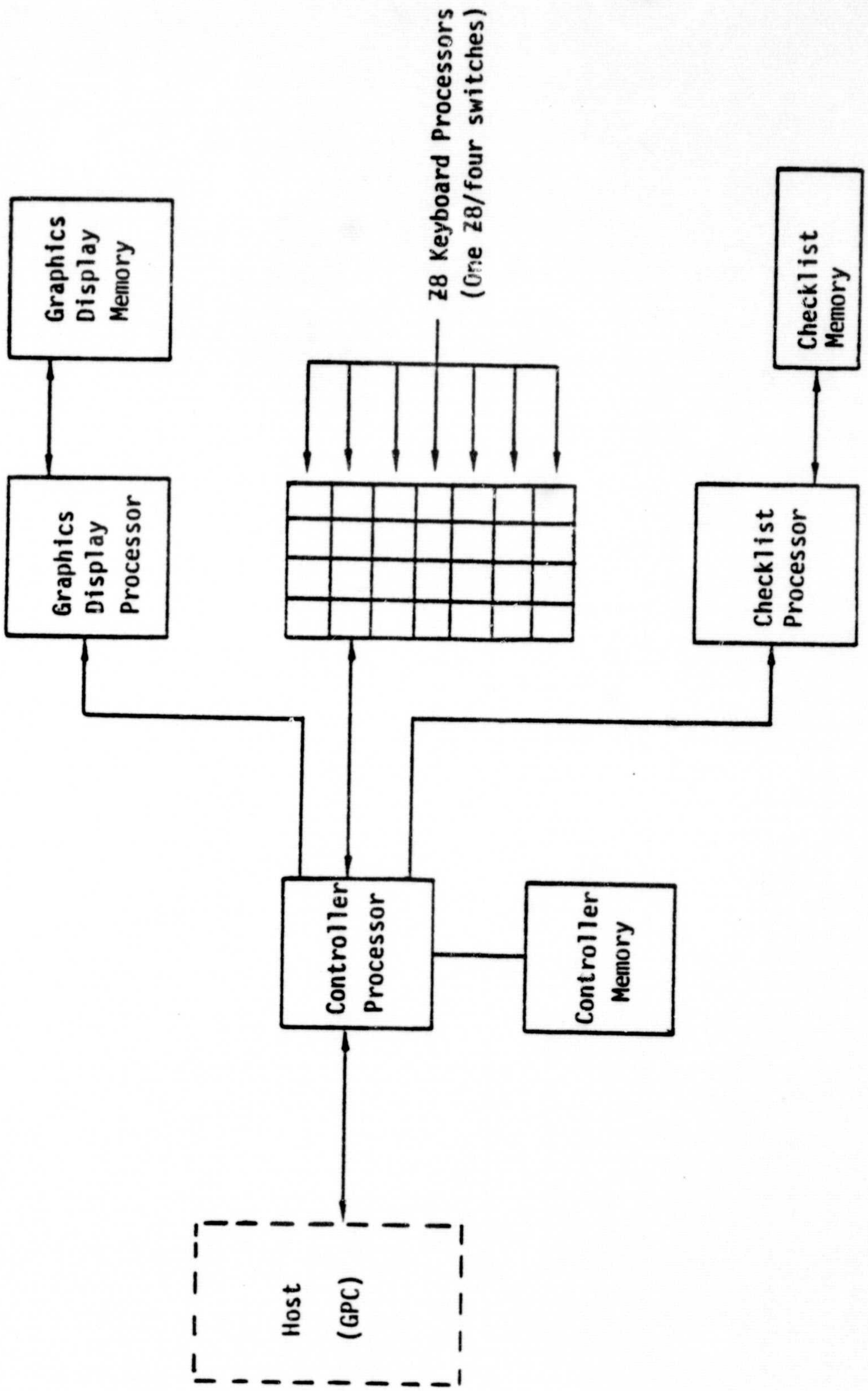


Figure 3.4-4 MFDCS PROCESSING ARCHITECTURE

8086) microprocessors respectively. The general analysis was part of another Boeing keyboard development program, but the OMS and EPDCS were used as examples for the results quoted in this report. The analysis makes the assumption of a serial RS 422 interface to each set of four switches and a serial line to the medium resolution display. These choices are discussed in Section 3.4.3. The analysis showed that for the assumed instruction mix and the interfaces chosen, the update rate for multifunction switches would be limited by transmission time for up to 20 switches for the 8085 and up to 40 switches for the 8086. Above this number of switches the throughput of the processor becomes the limiting factor as shown in Figure 3.4-5. Two cases were considered. The first was the time for pure alphanumerics and the second was the required update time for graphic displays on the switches.

These results were tested using a 8085 controller and a set of four switches as examples of the keyboard. Using the set of four and a data base designed for these four switches, the update time was measured. These results were found to be valid for up to 28 switches and an update time of 52ms for alphanumeric displays was obtained. For pattern map displays the estimated time to update the keyboard is longer and was measured at 250ms. Most keyboards will use a mix of symbols and alphanumerics and the total mix updte time should be $\leq$ 0.2 seconds. The update tests are described in Section 4.

A limited test of a TFEL medium resolution panel was conducted using both a graphic and an alphanumeric display. The results showed an update time of 608ms for alphanumeric data and $<$250ms for a graphic display. This test employed a shared bus structure and would result in slower update times than those for a dedicated processor. This relation for the various interface/options is shown in Figure 3.4-6.

A good example of a high resolution color display suitable for inclusion in the MFDCS was not available. Tests were conducted on the update rate of a small color video display. The results showed that an update rate for dynamic symbol modification of $\leq$ 0.2 second was achievable. In general, an update time of $\geq$30 frames/second is achieveable for high resolution stroke or raster graphic generation systems.

The same set of four switches was used to test the operation of the data base structure. The data base format was structured in the same way a larger keybord array would be handled. Each page of legends stored in the controller memory contains the command, if any, to the GPC, the vectors to legends to be displayed on the keybord and commands to the

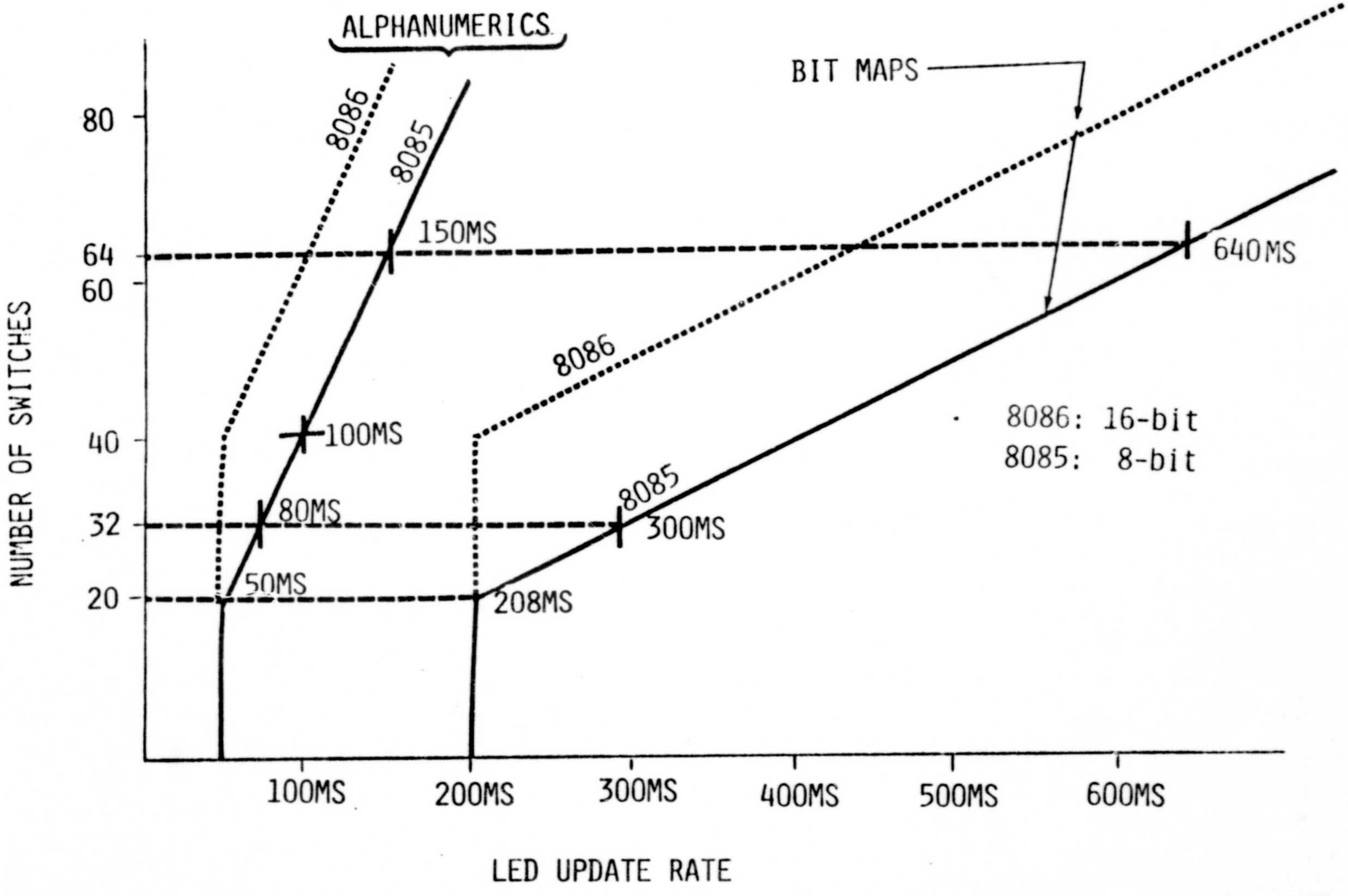


Figure 3.4-5 LED MFK VS NUMBER OF SWITCHES

8085 PROCESSOR

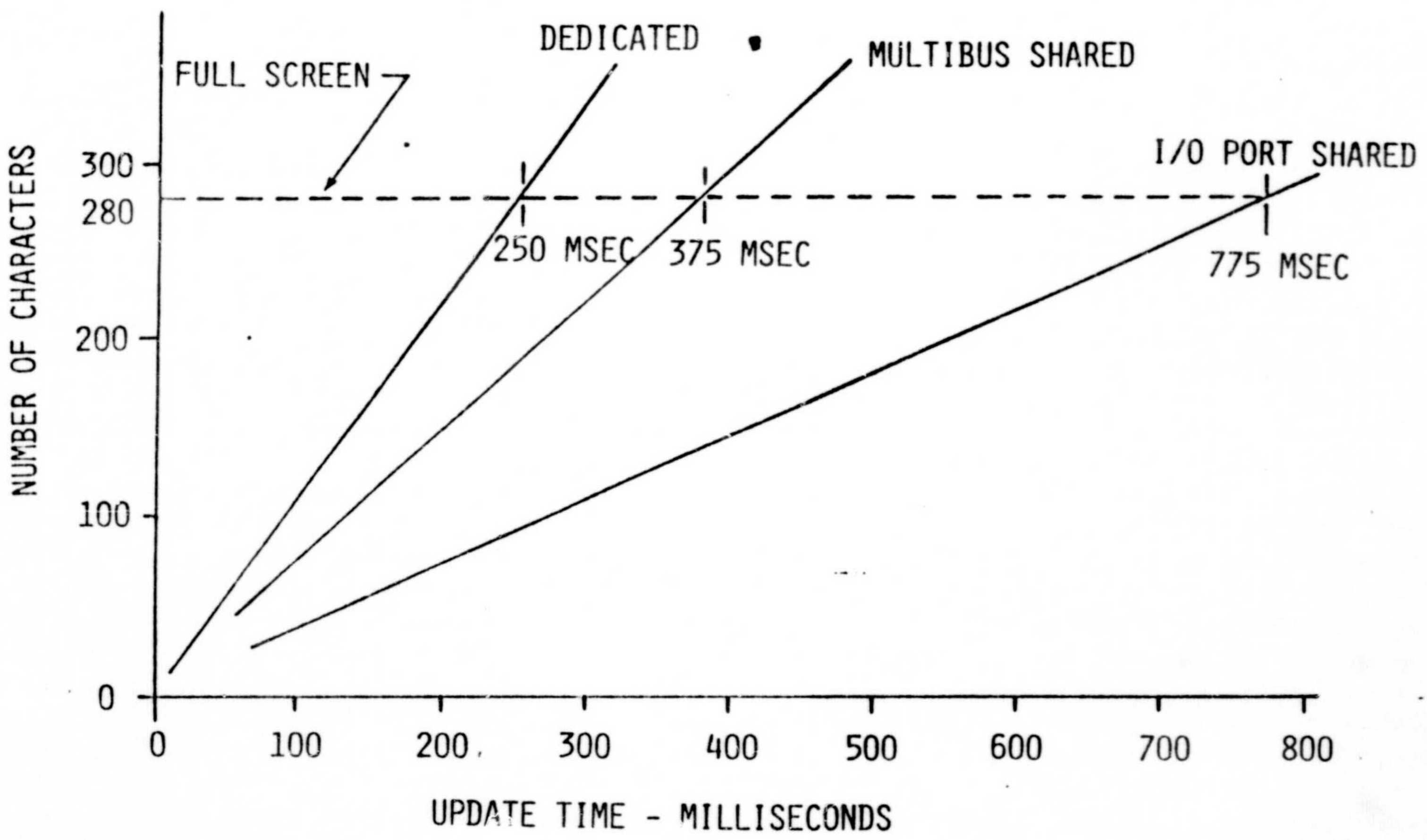


Figure 3.4-6 TFEL ALPHANUMERIC DISPLAY UPDATE RATE

medium and high resolution displays. Also included is the vector to the previous legend page. The 8085 controller was found to perform satisfactorily, displaying the appropriate legends in the correct logical sequence and transmitting the correct commands to the host. The test is described in Section 4. A 64k byte memory was found to be adequate for the controller data base storage and operating system.

3.4.3 Interface Analysis

The interfaces between the host and controller and between the controller and displays were analyzed to determine the type of data transfer to be used. Parallel and serial data line were investigated. The host (GPC)-controller interface will be defined by the access available to the data bus or GPC on the orbiter. The controller tested was designed to operate with an RS-232 interface with the intent of interfacing to a modular fashion to permit changes to the interface routines without changing the basic operating system.

The interfacing to the keyboard multifunction switches was investigated and an RS 422 serial line was selected to interface to each unit of four switches. A parallel line interface was found to be unnecessary with respect to required data transfer speed and required a larger number of wires between controller and keyboard. The RS 422 serial line was chosen over the RS 232 because it required a single 5 volt supply and provided a better driving capability for remote operation of the keyboard relative to the controller. An operating speed of 19.2kb was selected.

Interfacing to the medium and high resolution displays will depend on the display chosen. At this time the design developed places the processors for these two displays with the controller where they operate off a shared bus structure. The displays will be operated via serial (medium resolution) or video lines (high resolution).

4.0 Feasibility Testing

In this section of the report the tests conducted to resolve issues described in Section 3 (Design Analysis) are presented. A number of tests were conducted to determine display parameters, hardware/software capabilities and the validity of system concepts.

4.1 Display Resolution Requirements Test

All the design alternatives provide a schematic diagram capability for display of system configuration. A basic question is how large the display area must be and what level of resolution is necessary to provide the operator with adequate size and clarity of alphanumeric and graphic symbolism.

One of the test activities conducted was determination of the required display resolution. This determination was based on the assumption of a raster or discrete element display, with resolution specified in terms of discriminable display elements, or "pixels". It was also based on the assumption that pixel size and display viewing distance are such that the image detail that can be presented is limited primarily by the number of pixels available. The exception to this would occur when pixels are so small that even when there are a sufficient quantity present to clearly define the shape of a symbol, the symbol is still too small to be easily visible.

The answer to the question of resolution requirements depends on the information to be displayed. Display of a complete circuit diagram for the EPDCS would clearly require more resolvable elements than the display of the AC bus structure.

To arrive at a realistic test image, several graphic display images for use with an OMS and EPDCS MFDCS were developed. The image selected for use in the testing is near the upper limit of complexity in this set. It shows all the controllable valves in the OMS, the OMS fuel and pressurization sources, the OMS engines, the plumbing for normal and crossfeed operation, and at operator request, a portion of the pressure and temperature data for this system (Figure 3.4-1).

This image was evaluated using a monochrome CRT at a variety of sizes to simulate a square area containing 128 to 768 pixels on a side. A total of nine prints covering this range in equal-ratio steps was produced. For purposes of comparison, these nine prints were made

equal in size photographically; the resulting images are shown in Figures 3.4-3a through 3.4-3c.

These images were compared subjectively in terms of which provided sufficient resolution to easily distinguish essential features of the OMS such as valve status, valve number and which portions of the OMS plumbing contain fuel. On the basis of visual judgements by three observers, the 645 pixel display is the lowest resolution that achieves these goals.

4.2 Power Level Tests

Power levels were available for displays other than the LED multifunction switch displays. Tests were conducted on a set of four LED multifunction switches to determine the power levels required to drive displays of this type. The power levels represent typical values for sunlight readable flat panel green LED arrays currently being evaluated for use in tactical aircraft. Power levels measured are shown in the upper section of Figure 4.2-1 and assume a 25% fraction of LED's lit within the display area of 2.2 cm^2 (.35 in^2). These figures define the LED flat panel power level discussed in Section 3.4. The switches used for this test can display up to two rows of 6 alphanumeric characters in a 5 X 7 font with a .063cm pixel spacing (40 lines/inch). The lower portion of Figure 4.2-1 shows the display power levels recorded for 11 and 12 character legend examples. Note that for this number of characters the power level and number of diodes lit is somewhat higher than the 25% figure assumed. These power levels are within the upper level predicted in the design however the 25% figure for the fraction of LED's lit in an alphanumeric display would appear to be too low for a legend with two rows of 5 or 6 characters.

Switch No.	Display Pattern	Display Voltage Reading per Switch	Display Current Reading per Switch	Display Power per Switch	Total LRCU Power
1	140 LEDS*	5.18 VDC	146 ma	756.3 mw	
2	140 LEDS	5.18 VDC	172 ma	891. mw	3.12W
3	140 LEDS	5.18 VDC	146 ma	756.3 mw	
4	140 LEDS	5.18 VDC	142 ma	735.6 mw	
1	11 A/N char	5.18 VDC	172 ma	891 mw	
2	11 A/N char	5.18 VDC	182 ma	942.8 mw	
3	12 A/N char	5.18 VDC	196 ma	1015.3 mw	3.76 W
4	12 A/N char	5.18 VDC	175 ma	906.5 mw	

*Total number of diodes in an array is 560.

Figure 4.2-1 LED MULTIFUNCTION SWITCH

4.3 Reaction Time Tests

A test on the reaction time for an array of four multifunction switches was conducted. This test serves as a benchmark for the evaluation of the validity of the hardware/software analysis for the various multifunction keybord architecture options analyzed in Section 3.4. In this test, the time between activation of a switch and the appearance of a new set of legends on the switches was measured. The test employs a serial line to drive a set of four switches. Test results show an update time of 52ms to update the set of four switches with an alphanumeric legend and 250ms to update the same switches with a special graphics pattern on each switch. Those figures compare reasonably well with the estimates obtained for the analysis of architecture options shown in Figure 3.4-5.

4.4 Display Image Modification Test

The schematic displays developed for the OMS and EPDCS MFDCS require a dynamic update capability for active elements (valves, switches, parameters etc.) within the display. The capability of a small microprocessor based system to handle the display modification was tested using symbols of several sizes to indicate the active elements in a schematic system. The selective modification was done by storing the various schematic symbol options and placing the appropriate option (e.g. a closed vs. open valve symbol) in the designated

locations on the schematic. The update time was found to be acceptable $\leq$0.5 seconds using a microcomputer operating at a clock rate of 0.9 MHz.

4.5 Data Base Test

Using the same set of four multifunction switches, a controller was programmed to operate the four switches using a data base devised for the set of four. This test was performed as a check on the validity of the logic structure, legend storage and command structure associated with the larger data base developed for the OMS and EPDCS MFDCS. Performance of all functions of the four switch data base were found to operate satisfactorily.

4.6 Color Coding

A study of various interactive schematics associated with system management of the OMS and EPDCS revealed that some were necessarily quite complex. Sample schematics were constructed on a GRAFTEK system and printed in black and white. These schematics are intended to show subsystem status, that is, they are dynamic in that they display the total subsystem effect of opening or closing a switch or valve. The objective was to develop a schematic which would pictorially reveal to the operator, at a glance, the exact status of that subsystem or subsystem segment in real time. In the black/white version, energized circuits or flow path plumbing was shown as bold solid lines and unenergized non-flow path circuits and plumbing was shown as thinner broken lines. With a little study by the observer, system status was readily understood. However, when system parameters were overlaid on the display in black and white, the clutter was increased and some displays were considered marginal in terms of rapid comprehension.

Color coding was then added to the displays. Energized circuits or flow path plumbing was shown as solid green lines; unenergized circuits or non-flow path plumbing was shown as broken B/W lines; out-of-limit parameters or disabled system elements were shown in yellow or orange and normal system parameters were displayed in megenta. Red was reserved for critical functions or dangerous parameter status.

Subjective comparison of the two displays revealed a marked improvement in readability and clutter relief of the color coded version. As a result of this study, color coded displays are recommended with default to the B/W version.

5.0 PRESENTATION OF RESULTS

The analyses of testing of design alternatives resulted in a basic verification of system capability. At the same time, a number of areas were felt to require further resolution. These areas are discussed in Section 5.2.

5.1 MFDCS Capabilities Summary

The capabilities built into the MFDCS design and the results of the analyses of hardware/software design options are presented in the following subsections.

5.1.1 Access Schema

Results of the functional analysis of the OMS and EPDCS provided the input data for formulation of a logic access scheme and data base for the MFDCS design. The access scheme developed addresses the four major areas of concern developed during the earlier portions of the study. Information is presented to the crew on three displays. A high resolution color display appears best suited for the display of schematic diagrams while the use of flat panel displays for the display of checklists and a multifunction keyboard is suggested as a means of saving power, volume, and weight in the MFDCS.

Procedures and checklists are stored in the MFDCS memory for display to the crew members. The crew member has the option of processing the checklist or procedure either manually or automatically. Items on the list may be bypassed and covered later at operator option.

Another area of concern was the handling of caution and warning messages and malfunction procedures. With the design developed in this study, the array of caution and warning messages will be prioritized in terms of system impact and probable cause. Display of malfunctions will be accompanied by suggested procedures for dealing with the problem. The operator will be able to select which caution and warning alert is to be dealt with first as well as choosing an automatic or manual mode of handling the procedure. Once a procedure is selected, the method of handling the procedure is similar to that for non-alert checklists and procedures. The operator retains authority over the order in which the steps of the procedure are to be accomplished.

Preservation of operator access to the current individual functions was accomplished by the inclusion of another major operating mode for the MFDCS. In this mode the operator can access the current functions of the OMS and EPDCS on a function by function basis. Reference to the functions is made via a pictorial displav addressed by a multifunction keyboard. The pictorial display may be selected as an operator option in the two earlier operating modes.

Flexibility in the formation of the data base was viewed as an important feature of the system because of both changing mission requirements and possible changes in Orbiter hardware. The data base format has been structured to provide considerable flexibility in the logical linking and legends displayed on the keyboard, as well as in the commands passed to and data received from the host. For example, a new data base can be developed for each mission and downloaded to the MFDCS. A basic remaining question however is the degree of flexibility which can be permitted in modifying the data while still preserving configuration control over the system.

5.1.2 Hardware/Software Analyses

The basic architecture developed for the MFDCS uses a central processor in the controller to communicate with the host and the three display areas. Color was identified as a desirable feature and required the inclusion of a color CRT display for high resolution graphics. Power savings would result from the separation of the medium resolution and keyboard display areas and the use of flat panel displays for these areas. At this time, the available options would indicate use of an LCD for the medium resolution display and an array of LED multifunction switches for the keyboard. The switch choice is subject to modification as TFEL or LCD switches become available. The high and medium resolution displays will require their own memories and processors to control access to and display of the memory contents. The processors and memory will be located in the controller with separate output lines leading to the two displays. Each block of four LED switches will interface with the controller via its own microprocessor. Communication with the switches will be via serial data lines.

Analysis of response times for the system indicates a satisfactory response to operator interactions for the three displays. Keyboard update rates will in general be ≤ 0.2 seconds with a somewhat longer response for the medium resolution display of ~ 0.6 seconds. Dynamic update of the high resolution display can reduce to ≤ 0.2 seconds also with complete display changes requiring no more than 1 second.

The software design of the MFDCS is based on the assumption of an essentially stand-alone system duplicating as much as possible the interface of the present hardware to the GPC's. In addition, the software is structured so that the legends, displays and logical linkages of the data base are modifiable under software control. Multiple data bases may be used with the system by downloading the new data base from another memory location. This feature will permit system modifications for different missions or hardware.

For a direct application to an OMS and EPDCS MFDCS the installation will probably add both weight and power consumption because of the constraints imposed by hardware impact minimization.

5.1.3 System Function, Redundancy and Reliability

The MFDCS operation is limited to some extent by the inclusion of only the OMS and EPDCS in this study. Without access through the data bus to other system functions, a number of procedures cannot actually be automated since separate access to the other systems will be required.

Similarly, the reliability and redundancy of the system as a whole can be improved by combining the MFDCS for OMS and EPDCS into a general display and control system accessable by more than one crew member. Multiple keyboards and displays would then permit the exchange of faulty modules between the different crew stations.

5.2 Unresolved Issues

Several issues remain unresolved after the analysis and testing conducted under Task 3 and are described in the following subsections.

5.2.1 Light Levels

Ambient light in the Orbiter environment can vary from diffuse sunlight (10^4fc) to darkness (10^{-6}fc). During on orbit activities the direct sun may be effectively blocked out through orientation of the vehicle or window masks. However, during landing conditions the crew may have to work with a high ambient light level. The range of light levels present on the flight deck during the various mission phases will have a direct relation to the types of display which can be used. For example, the use of an LCD flat panel display requires

backlighting at low light levels. The savings in power realizable by using such a non-emissive display will be greatly affected by the time during which backlighting is required. Definition of the ambient and internal lighting will aid in display choice selection.

5.2.2 Touch Panels vs. Individual Switches

As indicated in earlier sections there are a number of ways to mechanize the operator control interface to an MFDCS, with two major modes being a touch panel tied into the processing system or a set of individual switches arranged in a keyboard. Both have been used as the basis for multifunction keyboards. Currently, the Orbiter switches include protection against inadvertent activation. To accomplish this protection using touch panels in the Orbiter might require an additional switch to activate the touch panel. Definition of required protection level and desired tactile feedback would also aid in control device choice selection.

5.2.3 Automation

Automation of procedures in the Orbiter can offer savings in crew workload, especially during periods requiring critical procedure accomplishment in a short time. The desired degree of automation will represent a combination of decisions based on the analysis of mission scenarios, the individual procedures and crew preference. These decisions need to be resolved before a final software configuration can be determined.

5.2.4 Trade-off Factors

The choice of components and architecture for the MFDCS depends to a significant extent on trade-offs between a number of factors. Thses include power, weight, volume, cost and training time. Establishement of the relative costs and weights of these factors will aid in the definition of the MFDCS design. For example, the reduction in training time, and hence training cost, could be related to the proposed development cost for a given MFDCS feature.

6.0 PROGRAM FOR TASK 4

During Task 4 (Design Recommendation) the conclusions reached during Task 3 and the discussions held during the Task 3 review will be used to develop the final design recommendation for the MFDCS design to control the OMS and EPDCS. Several areas need to be considered in the final design recommendation. Some of these will pertain specifically to the design features necessary to implement the design for the OMS and EPDCS MFDCS to be installed in the simulator. Other areas concern the application of the MFDCS to the Oribiter and/or other manned space operations in general.

6.1 Reliability and Redundancy

A primary feature required in the Orbiter is a high degree of reliability for each system as a whole. Reliability can be built into each part as far as possible. However most of the systems have also incorporated redundancy into their design. For example, the OMS systems uses two engines, but can operate with one while drawing fuel and oxidizer from either of two independent sets of tanks. Similar redundancy occurs in the EPDCS through the used of multiple fuel cells, busses and cross-tie options. The recommended MFDCS design must incorporate a similar redundancy capability (typcally three to four fold) and be shown to have the same or superior reliability relative to the present systems. With this goal in mind, the reliability of the recommended design will be outlined and suggestions made for providing redundancy in operation.

6.2 Packaging

The recommended design for the OMS and EPDCS must fit within the space available in the simulator. In Task 4 the components of this design will be grouped in a package to fit the available space. At the same time consideration will be given to cooling and power requirements as well as projected system weight.

6.3 Technology Status

The technology associated with displays and controls and in particular, multifunction displays and controls is advancing rapidly. The particular devices available depend, to a large extent, on the perceived market demand seen by the manufacturers. This situation is particularly true at this time in the field of flat panel displays of moderate size with the

flat screen television being the most obvious market targeted. The design recommended will use currently available technology, however the best technology choice will depend heavily on the exact time frame in which the design is to be built. Because the flat panel display offers potential advantages in terms of reduced volume weight and power, their use as a portion of the Orbiter MFDCS should be reviewed with respect to device performance and availability on a periodic basis. In Task 4 projections for future availability of some of the advantageous displays will be discussed.

6.4 General Orbiter Application of MFDCS Concepts

The work in Task 3 has been specifically directed towards a MFDCS operating the OMS and EPDCS and fitting within specific hardware and software constraints as discussed earlier in this report. However, the MFDCS concepts developed are readily adaptable to many of the other Orbiter systems. In general, the level of automation would be enhanced by the inclusion of additional systems. At the same time, the MFDCS access could be improved and redundancy increased by changing the MFDCS location and configuration to permit access by a larger number of crew members. A general outline of these broader applications will be discussed in Task 4 and a possible layout will be presented.

6.5 Additional Manned Spaceflight Applications

A primary potential area for application of the MFDCS concept will be in the development of permanent space stations. A large number of systems and numerous varied operations will be carried out at such a facility and the use of an MFDCS could offer considerable savings in terms of weight and hardware complexity, as well as providing increased operator capability through automation of routine functions. It also offers significant improvements in flexibility over fixed designs because the functions performed in such a station will evolve throughout the life of the station, the optimal operator control/display interface cannot be permanently determined when the station is placed in orbit. Launching new control/display hardware to support each major change in function is costly. With a flexible MFDCS in place, the new operator interface can be redesigned and validated on the ground using an identical set of hardware and can be easily transported to the space station as a software data file. Some of the potential capabilities will be discussed in Task 4.

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APPENDIX A

ORBITER SYSTEM FUNCTIONS

C-2

TABLE A-1

OMS DISPLAY/CONTROL FUNCTIONS

SWITCHES	FUNCTION	DESTINATION	DISPLAY
		ENGINE CONTROL	
____________	(L) N2 TK P #1	GAUGE	GAUGE
____________	(L) N2 TK P #2	GPC-MCC	GNC SYS SUMM 2
____________	(R) N2 TK P #1	GAUGE	GAUGE
____________	(R) N2 TK P #2	GPC-MCC	GNC SYS SUMM 2
(L) OFF, ARM, ARM/PRESS	(L) N2 PRESS VLV POSITION	GPC-MCC	GNC SYS SUMM 2
(R) OFF, ARM, ARM/PRESS	(R) N2 PRESS VLV POSITION	GPC-MCC	GNC SYS SUMM 2
(L) ENG VLV SWITCH (014)	(L) SWITCH POS	GPC-MCC	____________
(R) ENG VLV SWITCH (016)	(R) SWITCH POS	GPC-MCC	____________
(GPC)	(L) BALL VLV POS %	GPC-MCC	GNC SYS SUMM 2
(GPC)	(R) BALL VLV POS %	GPC-MCC	GNC SYS SUMM 2

TABLE A-1 (CONTINUED) SHEET 2

SWITCHES	FUNCTION	DESTINATION	DISPLAY
____________	(L) N2 TK REG PRESS	GPC-MCC	GNC SYS SUMM 2
____________	(R) N2 TK REG PRESS	GPC-MCC	GNC SYS SUMM 2
____________	(L) FU INJ TEMP	GPC-MCC	GNC SYS SUMM 2 PASS PRPLT THERMAL
____________	(R) FU INJ TEMP	GPC-MCC	GNC SYS SUMM 2 PASS PRPLT THERMAL
____________	(L) CHAMB PRESS	GPC-MCC GAUGE	GAUGE
____________	(R) CHAMB PRESS	GPC-MCC GAUGE	GAUGE
____________	(L) FU IN PRESS	GPC-MCC	GNC SYS SUMM 2
____________	(R) FU IN PRESS	GPC-MCC	GNC SYS SUMM 2
____________	(L) OX IN PRESS	GPC-MCC	GNC SYS SUMM 2
____________	(R) OX IN PRESS	GPC-MCC	GNC SYS SUMM 2

TABLE A-1 (CONTINUED) SHEET 3

SWITCHES	FUNCTION	DESTINATION	DISPLAY
	BIPROPELLANT CONTROL		
(L) TK ISOL FU A	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(L) TK ISOL OX A			PANEL 08
(L) TK ISOL FU B	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(L) TK ISOL OX B			PANEL 08
(L) X FEED FU A	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(L) X FEED OX A			PANEL 08
(L) X FEED FU B	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(L) X FEED OX B			PANEL 08
(K) TK ISOL FU A	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(K) TK ISOL OX A			PANEL 08
(K) TK ISOL FU B	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(K) TK ISOL OX B			PANEL 08
(R) TK ISOL FU A	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY

TABLE A-1 (CONTINUED) SHEET 4

SWITCHES	FUNCTION	DESTINATION	DISPLAY
(R) TK ISOL OX A			PANEL 08
(R) TK ISOL FU B	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(R) TK ISOL OX B			PANEL 08
(R) X FEED FU A	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(R) X FEED OX A			PANEL 08
(R) X FEED FU B	OPEN/CLOSE STATUS	GPC	OPEN/CLOSE DISPARITY
(R) X FEED OX B			PANEL 08
(L) PRESS/VAPOR ISOL A	OPEN/CLOSE STATUS	GPC	ALERT (FDI BURN CHECK)
(L) PRESS/VAPOR ISOL B	OPEN/CLOSE STATUS	GPC	ALERT (FDI BURN CHECK)
(R) PRESS/VAPOR ISOL A	OPEN/CLOSE STATUS	GPC	ALERT (FDE BURN CHECK)
(R) PRESS/VAPOR ISOL B	OPEN/CLOSE STATUS	GPC	ALERT (FDI BURN CHECK)
(K) PRESS/VAPOR ISOL A	OPEN/CLOSE STATUS	GPC	ALERT (FDI BURN CHECK)
(K) PRESS/VAPOR ISOL B	OPEN/CLOSE STATUS	GPC	ALERT (FDI BURN CHECK)

TABLE A-1 (CONTINUED) SHEET 5

SWITCHES	FUNCTION	DESTINATION	DISPLAY
____________	(L) OX TK PRESS	GPC MCC	METER (P03) GMC SYS SUMM 2
____________	(R) OX TK PRESS	GPC MCC	METER GNC SYS SUMM 2
____________	(L) FU TK PRESS	GPC MCC	METER GNC SYS SUMM 2
____________	(R) FU TK PRESS	GPC MCC	METER GNC SYS SUMM 2
____________	(K) OX TK PRESS	GPC MCC	METER GNC SYS SUMM 2
____________	(K) FU TK PRESS	GPC MCC	METER GNC SYS SUMM 2
____________	HE TK PRESS	PANEL F7	METER (F7)
____________	HE TK PRESS	GPC MCC	GNC SYS SUMM 2
ROTARY SWITCH	(L) FU QTY	PANEL 03	METER
ROTARY SWITCH	(R) FU QTY	PANEL 03	METER

TABLE A-1 (CONTINUED) SHEET 6

SWITCHES	FUNCTION	DESTINATION	DISPLAY
ROTARY SWITCH	(K) FU QTY	PANEL 03	METER
ROTARY SWITCH	(L) OXID QTY	PANEL 03	METER
ROTARY SWITCH	(R) OXID QTY	PANEL 03	METER
ROTARY SWITCH	(K) OXID QTY	PANEL 03	METER
THERMAL CONTROL			
(L) POD HTR A (L) POD HTR B (R) POD HTR A (R) POD HTR B (K) HTR A XFEED HTR A XFEED HTR B	TEMPERATURES LIMIT SENSED	GPC MCC	ANNUNCIATORS BFS SM OPS THERMAL PRLT THERMAL

TABLE A-1 (CONTINUED) SHEET 7

SWITCHES	FUNCTION	DESTINATION	DISPLAY
	THRUST VECTOR CONTROL		
	CURRENT GIMBAL PITCH AND YAW ANGLES LEFT AND RIGHT	GPC MCC	XXXX MNVR YYYY
KEYBOARD/CRT	LOAD GIMBAL PITCH AND YAW ANGLES LEFT AND RIGHT	GPC MCC	XXXX MNVR YYYY
KEYBOARD/CRT	PRIM AND SECOND DRIVE	GPC MCC	XXXX MNVR YYYY
KEYBOARD/CRT	GIMBAL CHECK	GPC	XXXX MNVR YYYY

TABLE A-2

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		MAIN BOS & TIE		
FC/MN BUS A	--	R1	ON/OFF	CONTR STATUS R1
MN BUS TIE A	--	R1	ON/OFF	CONTR STATUS R1
--	MNA CONTR	013	ESS 1 BC	--
FC/MN BUS B	--	R1	ON/OFF	CONTR STATUS R1
MN/BUS TIE	--	R1	ON/OFF	CONTR STATUS R1
--	MN B CONTR	013	ESS 2 CA	--
FC/MN BUS C	--	R1	ON/OFF	CONTR STATUS R1
MN/BUS TIE C	--	R1	ON/OFF	CONTR STATUS R1
--	MN C CONTR	013	ESS 3 AB	--
--	--	CRT	FC/MN VOLTS/AMPS	SM OPS 2 ELECTRICAL

TABLE A-2 (SHEET 2)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		MAIN BUS & TIE		
--	--	CRT	FC/MN VOLTS/AMPS TOTAL AMPS	SM OPS 2 SM SYS SUMM 1
--	--	CRT	FC/MN VOLTS/AMPS TOTAL AMPS	BFS SM SYS SUMM 1
		ESS BUS		
MN B/C	--	R1	ON/OFF	--
FC 1	--	R1	ON/OFF	--
MN C/A	--	R1	ON/OFF	--
FC 2	--	R1	ON/OFF	--
MN A/B	--	R1	ON/OFF	--
FC 3	--	R1	ON/OFF	--

TABLE A-2 (SHEET 3)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		CONTROL BUSES		
MN A	--	R1	RESET RPC	--
MN B	--	R1	RESET RPC	--
MN C	--	R1	RESET RPC	--
--	--	CRT	CNTRL BUS	SM OPS 2 ELECT VOLTS
--	--	CRT	CNTRL BUS	SM OPS 2 SYS SUMM 1 VOLTS
--	--	CRT	CNTRL BUS	BFS SM SYS SUMM 1 VOLTS
		AC POWER		
AC BUS SNSR -1	--	R1	NOW/OFF/AUTO TRIP	--
INV/AC BUS -1	--	R1	ON/OFF	STATUS R1
INV PWR -1	--	R1	ON/OFF	STATUS R1

TABLE A-2 (SHEET 4)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		AC POWER		
--	AC 1 SNSR	013	ESS 1 BC	--
--	AC CONTR 10A	R1	ESS 1 BC	--
--	AC CONTR 10B	R1	ESS 1 BC	--
--	AC CONTR 10C	R1	ESS 1 BC	--
AC BUS SNSR -2	--	R1	MON/OFF/AUTO TRIP	--
INV/AC BUS -2	--	R1	ON/OFF	STATUS R1
INV PWR -2	--	R1	ON/OFF	STATUS R1
--	AC 2	013	ESS 2 CA	--
--	AC CONTR 20A	R1	ESS 2 CA	--
--	AC CONTR 20B	R1	ESS 2 CA	--
--	AC CONTR 203	R1	ESS 2 CA	--
AC BUS SNSR -3	--	R1	MON/OFF/AUTO TRIP	--

TABLE A-2 (SHEET 5)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		AC POWER		
INV/AC BUS -3	--	R1	ON/OFF	STATUS R1
INV PWR -3	--	R1	ON/OFF	STATUS R1
--	AC 3 SNSR	013	ESS 3AB	--
--	AC 3 CONTR 3ϕA	R1	ESS 3AB	--
--	AC 3 CONTR 3ϕB	R1	ESS 3AB	--
--	AC 3 CONTR 3ϕC	R1	ESS 3AB	--
--	--	CRT	AC VOLTS/AMPS	SM OPS 2 ELECTRIC
--	--	CRT	AC VOLTS/AMPS	SM OPS 2 SYS SUMM 1
		FORWARD MOTOR CONTROL		
MCA LOGIC - A #1	--	MA73C	ON/OFF	--
--	MCA PWR AC1 - 30 FWD 1	MA73C	AC10A - 0C	--

TABLE A-2 (SHEET 6)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		FORWARD MOTOR CONTROL		
--	FWD RCS 1 VLV ØA	MA73C	AC10A	--
--	FWD RCS 1 VLV ØB	MA73C	AC 1 0B	--
--	FWD RCS 1 VLV ØC	MA73C	AC 1 0B	--
MCA LOGIC -B #2	--	MA73C	ON/OFF	--
--	MCA PWR AC1-3Ø FWD 2	MA73C	AC 2 0A - 0C	--
--	FWD RCS 2 VLV ØA	MA73C	AC20A	--
--	FWD RCS 2 VLV ØB	MA73C	AC20B	--
--	FWD RCS 2 VLV ØC	MA73C	AC20C	--

TABLE A-2 (SHEET 7)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		FORWARD MOTOR CONTROL		
MCA LOGIC -C #3	--	MA73C	ON/OFF	--
--	FWD RCS 3 VLV ØA	MA73C	AC30A	--
--	FWD RCS 3 VLV ØB	MA73C	AC30B	--
--	FWD RCS 3 VLV ØC	MA73C	AC30C	--
--	MCA PWR AC1 - 3Ø FWD 3	MA73C	AC30A - OC	--
		MID MOTOR CONTROL		
MN A/MID 1 LOGIC	--	MA73C	ON/OFF	--
MN B/MID 1 LOGIC	--	MA73C	ON/OFF	--
--	MID 1 PWR AC1 3Ø	MA73C	AC 1	--

TABLE A-2 (SHEET 8)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		MID MOTOR CONTROL (Cont'd)		
--	MID 1 PWR AC2 3Ø	MA73C	AC 2	--
MN B/MID 2 LOGIC	--	MA73C	ON/OFF	--
MN C/MID 2 LOGIC	--	MA73C	ON/OFF	--
--	MID 2 PWR AC2 3Ø	MA73C	AC 2	--
--	MID 2 PWR AC3 3Ø	MA73C	AC 3	--
MN A/MID 3 LOGIC	--	MA73C	ON/OFF	--
MN B/MID 3 LOGIC	--	MA73C	ON/OFF	--
--	MID 3 PWR AC1 3Ø	MA73C	AC 1	--
--	MID 3 PWR AC 2 3Ø	MA73C	AC 2	--
MN B/MID 4 LOGIC	--	MA73C	ON/OFF	--

TABLE A-2 (SHEET 9)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		MID MOTOR CONTROL (Cont'd)		
MN C/MID 4 LOGIC	--	MA73C	ON/OFF	--
--	MID 4 DWR AC 2 3Ø	MA73C	AC 2	--
--	MID 4 DWR AC 3 3Ø	MA73C	AC 3	--
		AFT MOTOR CONTROL		
MNA/AFT 1 LOGIC	--	MA73C	ON/OFF	--
AFT POP VLV LOGIC GP 1/3	--	MA73C	ON/OFF	--
AFT POD VLV LOGIC GP 1/2	--	MA73C	ON/OFF	--
--	AFT 1 PWR AC1 3Ø	MA73C	AC 1	--
--	AFT 1 -A POD VLV GP 1	MA73C	AC 1 0A	--

TABLE A-2 (SHEET 10)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		AFT MOTOR CONTROL (Cont'd)		
--	AFT 1 Ø B POD VLV GP 1	MA73C	AC1 ØB	--
--	AFT 1 Ø C POD VLV GP 1	MA73C	AC1 ØC	--
MNB/AFT 2 LOGIC	--	MA73C	ON/OFF	--
AFT 2 POD VLV LOGIC GP 1/3	--	MA73C	ON/OFF	--
AFT 2 POD VLV LOGIC GP 1/2	--	MA73C	ON/OFF	--
--	AFT 2 PWR AC2 3Ø	MA73C	AC 2	--
--	AFT 2 ØA POD VLV GP 1	MA73C	AC 2 ØA	--
--	AFT 2 ØB POD VLV GP1	MA73C	AC 2 ØB	--

TABLE A-2 (SHEET 11)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		AFT MOTOR CONTROL (Cont'd)		
--	AFT 2 ØC POD VLV GP 1	MA73C	AC 2 ØC	--
MNC/AFT 3 LOGIC	--	MA73C	ON/OFF	--
AFT 3 POD VLV LOGIC GP 1/3	--	MA73C	ON/OFF	--
AFT 3 POD VLV LOGIC GP 1/2	--	MA73C	ON/OFF	--
--	AFT 3 PWR AC 3Ø	MA73C	AC 3 0A-ØC	--
--	AFT 3ØA POD VLV GP1	MA73C	AC 3 ØA	--
--	AFT 3ØB POD VLV GP1	MA73C	AC 3 ØB	--
--	AFT 3ØC POD VLV GP1	MA73C	AC 3 ØC	--

TABLE A-2 (SHEET 12)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		PAYLOAD/CABIN		
PR1/FC3	--	RS	ON/OFF	STATUS R1
FC/MN BUS	--	R1	ON/OFF	STATUS R1
PR1/MN C	--	R1	ON/OFF	STATUS R1
PR1/MN B	--	R1	ON/OFF	STATUS R1
AUX	--	R1	ON/OFF	--
AFT/MN C	--	R1	ON/OFF	--
AFT/MN B	--	R1	ON/OFF	--
CABIN	--	R1	MN A/OFF/MNB	--
--	--	CRT	AFTB-C/DC AMPS	SM OPS 2 ELECTRIC

TABLE A-2 (SHEET 13)

EPDCS DISPLAY/CONTROL FUNCTIONS

SWITCH	C/B	LOC	FUNCTION	DISPLAY
		MISC		
ROTARY-9 POS	--	F9	AC VOLTS	METER
ROTARY-9 POS	--	F9	DC VOLTS DC AMPS/SIG STR	METER METER
AC 1 OMS KIT VLV LOGIV	--	MA73C	ON/OFF	--
--	AC1 OMS KIT ØA	MA73C	--	--
--	AC1 OMS KIT ØB	MA73C	--	--
--	AC1 OMS KIT ØC	MA73C	--	--
--	AC2 OMS KIT ØA	MA73C	--	--
--	AC2 OMS KIT ØC	MA73C	--	--
--	OMS KIT ØC	MA73C	--	--

ACTIVE SHEET RECORD

SHEET NO.	REV LTR	ADDED SHEETS				SHEET NO.	REV LTR	ADDED SHEETS			
		SHEET NO.	REV LTR	SHEET NO.	REV LTR			SHEET NO.	REV LTR	SHEET NO.	REV LTR
i						24					
ii						25					
iii						26					
iv						27					
v						28					
vi						29					
vii						30					
1						31					
2						32					
3						33					
4						34					
5						35					
6						36					
7						37					
8						38					
9						39					
10						40					
11						41					
12						42					
13						43					
14						44					
15						45					
16						46					
17						47					
18						48					
19						49					
20						50					
21						51					
22						52					
23						53					

THE BOEING COMPANY

ACTIVE SHEET RECORD

SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR	ADDED SHEETS SHEET NO.	REV LTR
54						84					
55						85					
56						86					
57						87					
58						88					
59						89					
60						90					
61						91					
62						92					
63						93					
64						94					
65						95					
66						96					
67						97					
68						98					
69						99					
70						100					
71						101					
72						102					
73						103					
74						104					
75						105					
76						106					
77						107					
78						108					
79						109					
80						110					
81						111					
82						112					
83											